Environmental impacts and risks of deep-sea mining

(MiningImpact 2)

Coordination: Dr. Matthias Haeckel

GEOMAR Helmholtz Centre for Ocean Research Kiel

Wischhofstraße 1-3, D-24148 Kiel, Germany

Phone: +49-431-600-2123

Email: mhaeckel@geomar.de

Project Schedule:	1 August 2018 – 28 February 2022 (43 months)
Research cruises:	February – May 2019 RV SONNE (98 days, monitoring of DEME nodule collector trial)
	Winter/Spring 2020/21 (to be proposed until 31.8.18, reconnaissance of collector trial impacts after 1-2 years)

Table of Contents

1. Introduction

The last decade has seen a steady increase of interest in mining of deep-sea minerals, as documented, for example, by the growing number of exploration contracts issued by the International Seabed Authority (ISA) and the “Blue Growth” strategy of the EU’s Horizon2020 program funding marine mining technology projects, i.e. Blue Mining, Blue Atlantis, and Blue Nodules. In this context, ISA is tasked with drafting of regulations for the exploitation of marine mineral resources in ‘the Area’ (the most recent version being ISBA/23/LTC/CRP.3*), which are anticipated to be ratified by the Council and the Assembly by 2020. Hence, it is timely to scientifically investigate the expected environmental impacts of deep-sea mining.

Impacts from mining activities on the marine environment will differ between resource types because polymetallic nodules and Co-rich crusts are essentially two-dimensional resources covering large areas of deep-sea surface sediments and seamounts, respectively (Hein and Koschinsky 2014), whereas massive sulfides form three-dimensional deposits extending tens to hundreds of meters into the subsurface (Hannington et al. 2011). However, two consequences appear to be common for the currently discussed mining technologies, the removal of the surface of the seafloor, including its epifauna, and the creation of a plume consisting of mineral debris and/or sediment that will blanket also some untouched seafloor in the vicinity of the mined area. While the EU-FP7 project MIDAS (www.eu-midas.net) addressed all three ore types, the JPIOceans-funded project MiningImpact (www.jpio-miningimpact.geomar.de), focused on impacts related to the harvesting of polymetallic nodules, particulary the longer-term (decadal) consequences.

Therefore, in MiningImpact 1 we investigated several disturbance tracks in ISA contract areas in the Clarion-Clipperton Fracture Zone (CCZ) in the NE Pacific (Martinez-Arbizu and Haeckel 2015), and we re-visited the DISturbance and reCOLonization area (DISCOL) in the Peru Basin in the SE Pacific (Greinert 2015, Boetius 2015). Both SONNE cruises, SO239 (CCZ) and SO242 (DISCOL), took place in 2015 targeting several decade-old impact sites. In the DISCOL area German scientists had conducted a benthic impact experiment (BIE) in 1989, ploughing 78 tracks in a circular area of ~11 km^2 of nodule-bearing seafloor, thereby disturbing approximately 20% of the seafloor. In contrast, the disturbances visited in the CCZ are much smaller, typically consisting of single or a few multiple tracks, a couple of meters wide and up to ~2 nm long, created by epi-benthic sleds or dredges.

Removal of the nodule habitat

Visual and hydroacoustic inspection of the disturbances in the CCZ and in the DISCOL area by AUV, ROV and OFOS identified prominent marks on the seafloor that are clearly visible even several decades after the tracks were created (e.g., 20 years for the IOM-BIE, 26 years for the DISCOL experiment, 37 years for the OMCO track), irrespective of their size. In this context it should be noted that commercial nodule mining intends to disturb continuous areas many times larger (potentially up to 200-250 km^2 per year per company) than the investigated scientific experiments.

Our results on the biological and geochemical situation at the disturbance sites are in line with previous studies that covered shorter time-scales of only 5-7 years after the impact (e.g. Thiel and Schriever 1990, Thiel et al. 2001). In general, epifaunal abundances, sessile fauna attached to the nodules (e.g., sponges, hydrozoa) and also mobile fauna associated to the nodule hard substrate (e.g., ophiuroids, isopods), are reduced in the CCZ tracks even decades after the impact was created (Fig. 1; Vanreusel et al. 2016). An equivalent picture can also be seen at DISCOL, where also a shift of the epifaunal community structure from dominatingly filter feeders (decreasing from 76% to 42%) to detritivores/predators (increasing from 20% to 49%) is observed (Marcon and Purser unpublished). Surprisingly, even the microbial communities do not seem to be capable of adapting to the seafloor disturbances within several decades, which is expressed, for example, in reduced metabolic activity and reduced oxygen consumption in the surface sediments (Vonnahme et al. in prep).

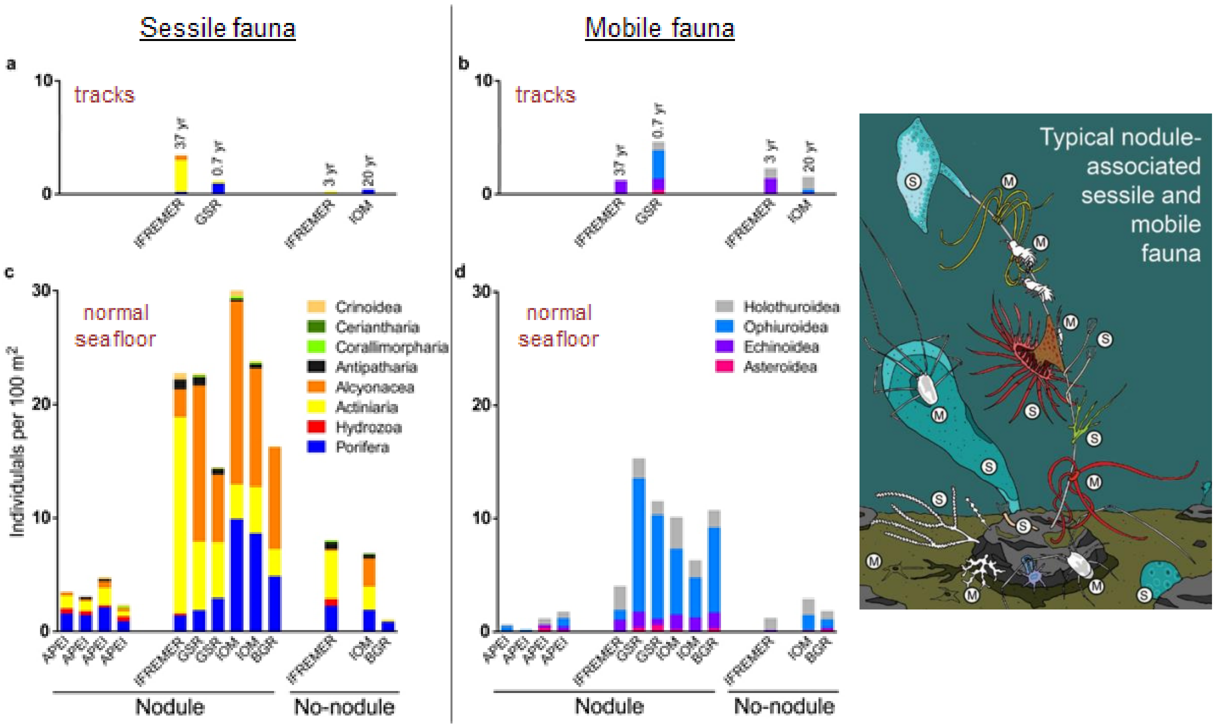


Figure 1: (left) Comparison of epifauna abundances (sessile and mobile) between various old disturbance tracks (1979 OMCO track, 1995 IOM-BIE, 2013 IFREMER EBS, 2015 GSR EBS) and normal deep-sea floor in CCZ areas w/o nodules (Vanreusel et al. 2016). (right) Sketch depicting the observed close association of mobile (M) and sessile (S) fauna to the nodules providing the necessary hard substrate (A. Purser, AWI).

Sediment plume dispersal

Previous mining tests (OMI/OMA in the 1970s) and benthic impact experiments (NOAA/Russia, JET, and IOM in the 1990s) in the CCZ have focused on determining the impact of the re-settled sediment plume on benthic fauna (e.g., Thiel et al. 2001), but they were not able to monitor the dynamic dispersal of the plume in the water column. Hence, our current knowledge on sediment dispersal is solely based on image analysis of seafloor blanketing (Yamazaki et al. 1997) and numerical simulations forced by time-series measurements of ocean bottom current velocities and directions and imposed grain size distributions and settling velocities (e.g., Nakata et al. 1997, Jankowski and Zielke 2001, Rolinski et al. 2001).

During SO239 and SO242 we conducted small-scale sediment dispersal experiments using an epibenthic sledge (EBS) or a remotely operated vehicle (ROV) to suspend surface sediment. We attempted to track the plume either by upward and downward looking acoustic Doppler current meters (ADCPs) mounted on benthic landers or light-backscatter sensors and HD cameras. While both experiments were not set up for quantitative analyses, some qualitative statements are still possible: (1) the sediment plumes seem to have risen not more than 10 m above the seafloor, and the lateral spread varied largely with current velocity and changing directions during the experiment as well as the seafloor topography. AUV mapping of the resettled sediment of the EBS experiment in the CCZ (Fig. 2 top) indicates that the major mass fraction of the suspended sediment covered nodules and epifauna up to 100 m to the south and up to 25 m to the north of the track. This observation is corroborated by controlled laboratory experiments documenting the importance of particle aggregation for scavenging of the fine fraction. Updated numerical simulations conducted in MiningImpact for the hydrodynamic conditions in the German contract area (Fig. 2 bottom) predict that industrial-scale plumes, releasing 100-1000 t/h, may spread at least 30 km from the source (equivalent to blanketing of >1 mm). While the impact of blanketing of the benthic ecosystem by the resettling sediment particles has been addressed in some of the BIEs (e.g., Radziejewska et al. 2001a+b, Radziejewska 2002) or by natural analogue studies (e.g., volcanic ash fallouts: Haeckel et al. 2001, Hess and Kuhnt 1996), we lack information on whether resuspended high particle concentrations and prolonged life-times of the plumes do harm the deep-sea fauna by e.g., clogging the filter feeding organs or releasing potentially toxic or oxygen-consuming substances. Upscaling of the small-scale experiments in these respects is very challenging and therefore, larger-scale experiments with realistic gear (e.g. industrial nodule collector) are needed to reduce current uncertainties with respect to the fate, dynamics and impact of the suspended sediment plume.

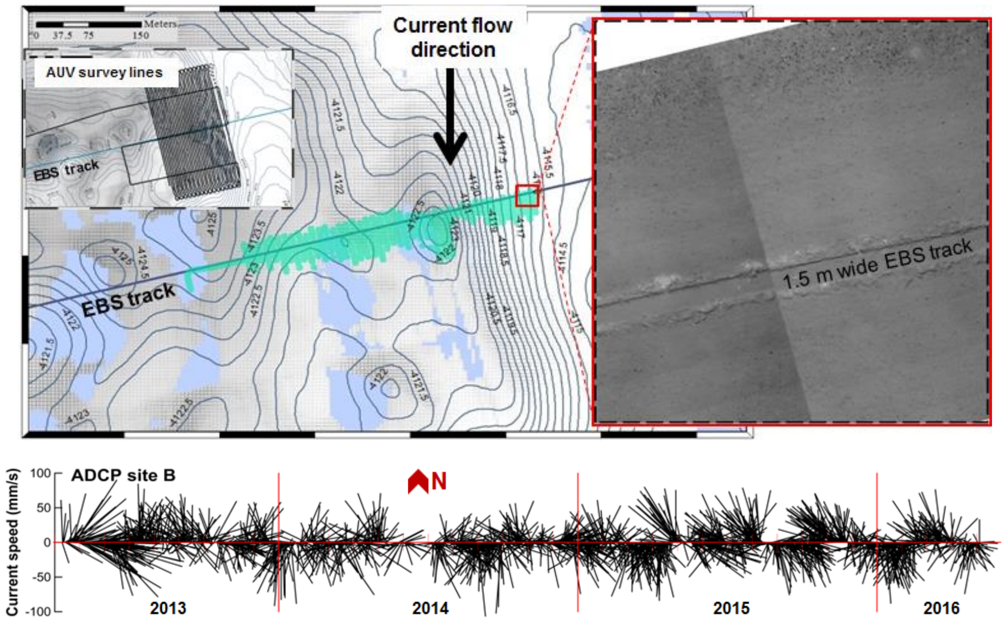


Figure 2: (top left) Map of the EBS sediment plume experiment in the German contract area. The resettled sediment was mapped (green area) based on an AUV photo mosaic. (top right) Zoom into the assembled photo mosaic taken by AUV Abyss showing the 1.5-m wide EBS track and the resettled sediment blanketing the nodules and epifauna on the adjacent seafloor. (bottom) 3 years (April 2013 to May 2016, measured 600-kHz ADCP data 12-16 m above the seafloor) of current data measured in the German contract area. Current velocities are typically <10 cm/s and directions are highly variable.

CCZ ecosystem baseline

During the first project phase, a comprehensive dataset of biological, biogeochemical, geological and oceanographic information was collected from the German, Belgian, French, and IOM contract areas as well as APEI3. These results form the ecosystem baseline for the intended work in the proposed second phase and, hence are summarized below.

The nodule surface is often inhabited by sessile metazoan epifauna, such as Hydrozoa, Anthozoa, and Porifera, resulting in higher epifaunal densities where nodule coverage is dense (Vanreusel et al. 2016). Also, smaller organisms belonging to the meiofauna size class, such as nematodes, harpacticoid copepods, tardigrades, and foraminiferan protists inhabit the crevices of nodules (Gollner et al. 2017). Several larger epifaunal, but also endofaunal species appear to be widespread across the CCZ (Janssen et al. 2015). Overall densities of sessile taxa in nodule areas are variable (14-30 individuals per 100 m^2; Fig.1). In nodule areas, anthozoans are the most abundant sessile group within the epifauna larger than 3 cm (>63 %), followed by sponges (Porifera, 6-36 %) (Fig.1). Mobile epifauna (>3 cm) was represented by echinoderms (Holothuroidea, Ophiuroidea, Echinoidea, and Asteroidea) in both, nodule-rich and nodule-free areas. Densities varied between 4-15 individuals per 100 m^2 among nodule-rich sites, largely due to the contribution of ophiuroids (Vanreusel et al. 2016). Densities of the mobile epifauna were more than two times lower on nodule-free sites

(1-3 ind./100 m^2) compared to nodule fields in the same geographical area, with a particularly large decrease (>50 %) in ophiuroids and echinoids (Vanreusel et al. 2016). In the soft sediment the dominant metazoan meiofaunal groups are nematodes, followed by harpacticoid copepods, while polychaetes and isopod crustaceans dominate the macrofaunal taxa, and typical megafauna comprises of ophiuroids, holothurians, fish and large komokiaceans and xenophyophore protists (Gollner et al. 2017). Diversity was found to be very high on local as well as CCZ-wide scale, and changes in benthic faunal composition, abundance, and diversity have been related to variations in surface primary productivity and the corresponding flux of organic carbon to the abyssal seafloor. Abundance and biomass of all faunal size classes (meio, macro- and megafauna) typically decrease along the productivity gradient from eutrophic to oligotrophic environments (Martinez-Arbizu & Haeckel 2015). This underlines the importance of benthic-pelagic coupling at the prospective mining sites and its potential negative effect on the benthos when naturally occurring phytoplankton and detritus arriving at the seafloor during times of plume dispersion aggregate and alter the dispersal pattern (Pabortsava et al. 2011, Purser and Thomsen 2012). Evidence of a wide geographic distribution exists for some genotypic clusters (e.g., polychaetes and isopods) that appear to be related not only to life history but also to distance (Janssen et al. 2015). However, assessing population and ecological connectivity across the CCZ is currently limited by low sample numbers, a patchy sampling scheme restricted to certain license areas within the CCZ, and the high proportion of undescribed species (Gollner et al. 2017).

Biogeochemical fluxes in the surface sediments follow the general trend of POC fluxes onto the seafloor decreasing from S to N and E to W across the CCZ. A good biogeochemical marker for this is the oxygen penetration depth that is around 2-3 m in the German license area (Mewes et al. 2014, Mogollon et al. 2016), increasing to 4 m and more in the French and Belgian license area and O_2 not being completely consumed in APEI 3. However, during SO239 significant spatial variations in the biogeochemical fluxes have been observed on km-scale and below within each license area. More importantly, in situ measurements of microbial POC degradation and respiration rates are currently missing and need to be performed during the proposed cruises in MiningImpact 2.

Time-series measurements of the hydrographic regime in the CCZ show that ocean bottom current velocities typically stay well below 10 cm/s and directions are highly variable (Fig. 2). Significant semi-diurnal (12 h), diurnal (24 h), and near-inertial (48-70 h) frequencies occur, and on longer time scales clockwise and anti-clockwise rotational flow with a 30-to-90-day frequency dominates (Fig. 2 bottom). Regularly, meso-scale eddies detach from the Mexican coast towards the CCZ (3-5 per year, particularly pronounced during El-Nino phases). With a lag time of 200-300 days they arrive in the German license area, where they can amplify bottom current velocities by a factor of 2-5 (as observed in April/May 2013; Aleynik et al. submitted), which would have a strong impact on plume dispersion and its deposition area.

Key conclusions from the first phase of MiningImpact are that (1) deep-sea ecosystems associated with polymetallic resources support a highly diverse fauna, (2) deep-sea faunal communities show a high variability on small and large spatial scales, but their connectivity over relevant scales for reference zones and for conservation remains unknown, (3) temporal variations of faunal abundances remain unknown due to the lack of long-term ecological time series, (4) loss of seafloor integrity by removal of nodules and surface seafloor reduces population densities and ecosystem functions (e.g. nutrient remineraliza-tion, microbial growth, bioturbation activity), (5) disturbance impacts last for at least many decades (e.g. biogeochemical processes will take >50 years to recover), and (6) sediment plumes will likely blanket the seafloor up to several 10s of kilometers outside the mined area.

Hence, minimizing the large-scale impacts from nodule mining will require careful adaptive spatial planning of mining operations and development of low-impact equipment. Environmental management plans need to address current uncertainties of the sediment plume dispersal and the specific spatial variability of the abyssal ecosystem that exists also on local scale. Technology for monitoring of the impacts is available, but concepts and sensors need to be developed and tested in the field during upcoming collector equipment and future pilot mining tests. This will also help to define indicator sets for “good” deep-sea ecosystem status and threshold values to avoid “harmful effects”.

2. Project Goals

In the second project phase of MiningImpact, we will extend our previous work towards three major research interests concerning deep-sea mining: (1) the larger scale environmental impact caused by the suspended sediment plume, (2) the regional connectivity of species and the biodiversity of biological assemblages and their resilience to impacts, and (3) the integrated effects on ecosystem functions, such as the benthic foodweb and biogeochemical processes. In this context, key objectives of the project are:

- To develop and test monitoring concepts and strategies for deep-sea mining operations
- To develop standardization procedures for monitoring and definitions for indicators of a good environmental status
- To investigate potential mitigation measures, such as spatial management plans of mining operations and means to facilitate ecosystem recovery
- To develop sound methodologies to assess the environmental risks and estimate benefits, costs and risks
- To explore how uncertainties in the knowledge of impacts can be implemented into appropriate regulatory frameworks

While the first project phase could investigate only experimental and/or rather small-scale disturbances of the seafloor, in the second phase a comprehensive monitoring program will be devoted to the industrial test of the prototype nodule collector system of the Belgian contractor DEME-GSR. The test intends to harvest nodules in approx. 300x300-m^2 large areas of the seabed in the Belgian and the German contract areas of the CCZ. Thus, MiningImpact 2 will collect independent scientific information on the environmental impacts of this operation. Here, the primary focus is on constraining and quantifying the temporal dynamics and characteristics of the suspended sediment plume, the spatial footprint of the deposited sediment blanket, and the induced effects on the abyssal ecosystem.

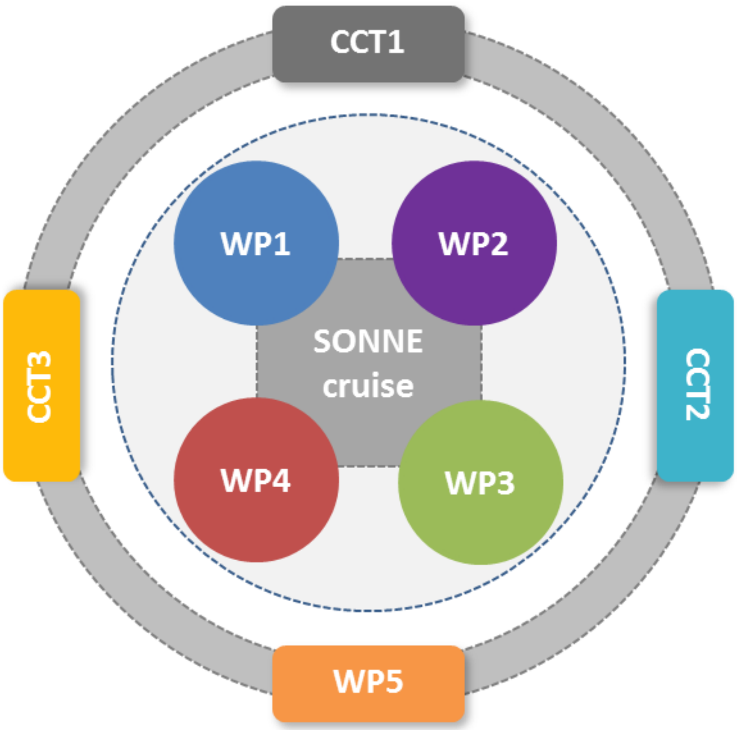
Thus, MiningImpact 2 will be able to further close existing knowledge gaps and reduce uncertainties on the environmental impacts of deep-sea mining of polymetallic nodules. The project will specifically work towards policy recommendations and, therefore, has reached out to the International Seabed Authority (ISA) to become a partner in the project. These overall aims are also reflected in the project structure (Section 3): three work packages (WPs) address the biodiversity, connectivity and resilience of biological assemblages (WP1), the impact and behaviour of the sediment plume (WP2), and benthic ecosystem functions and processes (WP3), while WP4 facilitates data exchange and archival in the project and develop advanced video/photo annotation technology. Three cross-cutting themes (CCTs) ensure integration of the different aspects into a coherent work flow at sea to accomplish an effective monitoring of the collector trial (CCT1), of the scientific results into a comprehensive assessment of the environmental impacts (CCT2), and into joint policy recommendations on risks and best practices of deep-sea mining operations (CCT3). WP5 will coordinate the project activities and communicate and disseminate project results.

Added value: As in the first project phase, MiningImpact 2 continues to effectively combine the existing scientific expertise on the deep-sea ecosystem across Europe to answer the above research questions. To achieve the challenging task of monitoring of deep-sea mining operations, it is also necessary to deploy the available state-of-the-art equipment of Europe’s leading oceanographic institutions on joint research cruises to gain the most, in terms of samples and data, from the limited ship time available. The project will directly contribute to the preparation of environmental impact assessments (EIAs) for future European deep-sea pilot mining tests that are requested by ISA and to the Horizon2020 technology development projects Blue Atlantis and Blue Nodules. MiningImpact 2 will open up new avenues for industry engaging in deep-sea monitoring, and it will continue to build an integrated research community on deep-sea mining, including disciplines, such as law and economics.

More specific objectives are outlined in the individual WP/CCT descriptions in Section 4, including details on how *the state of the art* will be advanced and on how the *work program* supports the achievement of these goals.

3. Work Program

3.1 Project Structure



WP1 Biodiversity, connectivity, resilience

WP2 Fate and toxicity of the sediment plume

WP3 Biogeochemistry and ecosystem functioning

WP4 Data and sample management

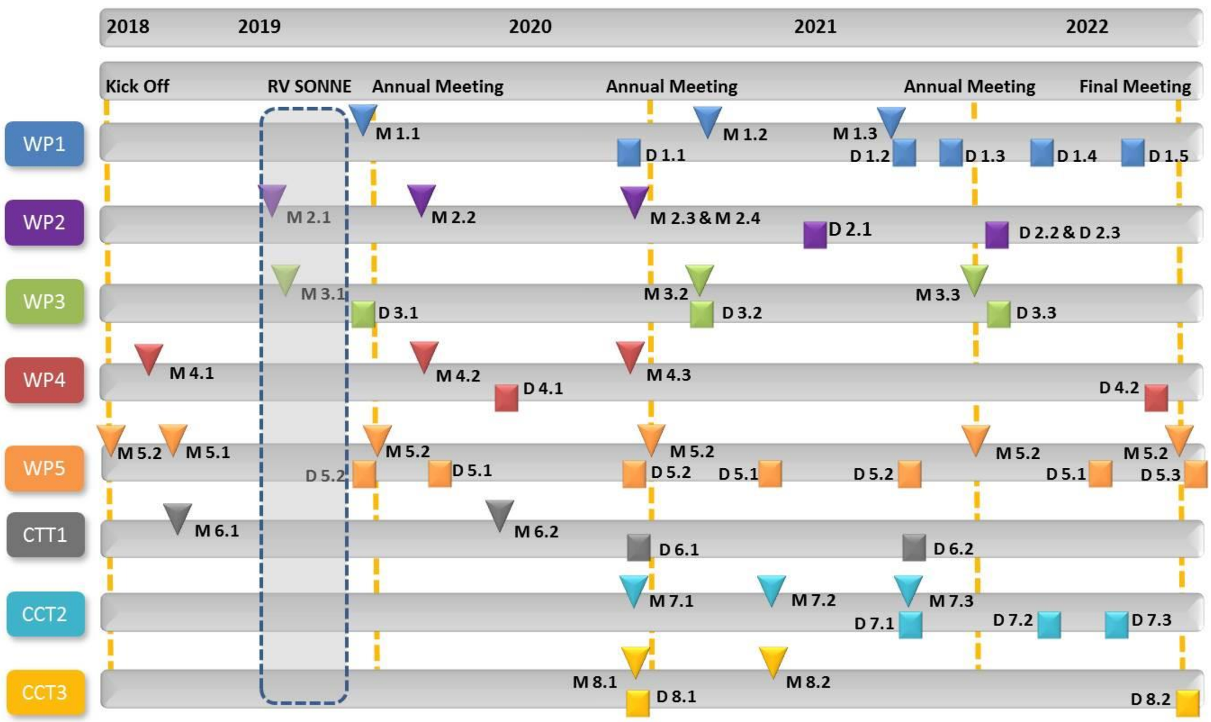
WP5 Project dissemination and coordination

CCT1 Plume monitoring and habitat/disturbance characterization

CCT2 Disturbance effects in time and space

CCT3 Environmental risk assessment & policy recommendations

3.2 Gantt Chart



3.3 List of Project Milestones and Deliverables (in chronological order)

No	Milestone Description	Expected Month	Responsible Partner
M 5.2	Annual project meetings	yearly	GEOMAR
M 4.1	Data policy, including schedule for data sharing, archival, and open access, is agreed on by all partners	3	GEOMAR
M 5.1	Communication plan and website launch	2	GRIDA
M 6.1	Planning of SONNE cruise and EMMP layout	4	GEOMAR
M 2.1	Plume monitoring sampling and experiments successfully conducted during SONNE cruise	9	NIOZ
M 3.1	Sampling, in situ measurements and experiments conducted successfully during baseline and impact cruise	9	MPI
M 1.1	Sampling and survey activities completed and metadata supplied to data archive	12	IMAR
M 8.1	Description of the structure of the models showing how the data from the collector trial will be integrated into the models	12	UAlgarve
M 2.2	Setup of numerical models for near-field and far-field plume dispersion	15	MARUM & TUDelft
M 4.2	Shared datasets are made available to all project partners via OSIS-Kiel, PANGAEA, BIIGLE, Vidlib & internal project website	15	GEOMAR
M 6.2	Evaluation of employed EMMP concept and monitoring technology	18	JUB
M 2.3	Data from plume monitoring array, seabed image analysis, plume particle dynamics, plume trace metal reactions processed & ready for integration in plume dispersal & geochemical models	24	GEOMAR & JUB
M 2.4	Workshop on the spatial and temporal ecological effects of the plume to identify suitable impact indicators	24	UAlgarve
M 4.3	Geospatial browsing and video annotation tool have been tested successfully	24	UBielefeld
M 7.1	Workshop on quantitative assessment of intensities, incl. scoring criteria of pressures + responses of ecosystem components	24	UGhent, AWI
M 3.2	Biogeochemical sediment characteristics, fluxes, organic matter processing by benthic communities including baseline variability & quantified impact effects, provided for integration in CCT2	27	CIIMAR & MPI
M 1.2	Sequencing and imaging data submitted to public data archives and shared among project participants	28	UAveiro
M 7.2	Workshop on scales, indicators and tresholds	30	SGN & IFREMER
M 8.2	Validation of WOE model achieved, recommendation on this methodology ready to be incorporated into guidance document	30	DNV
M 1.3	Benthic assemblage biodiversity data across size classes disseminated to CCT2 for integrated analysis	36	UGhent
M 7.3	Workshop on integrated analysis of ecosystem responses and environmental impact assessment	36	UAlgarve
M 3.3	Setup of food-web and diagenetic models and first simulations results discussed with project partners	39	NIOZ & GEOMAR

No	Deliverable Description	Month of Delivery	Responsible Partner
D 3.1	First results and data from field work, in situ and experimental studies are made available to project partners	12	MPI
D 5.2	Publication of focused project reports on WP and CCT topics	12+24+36	GRIDA, GEOMAR
D 5.1	ISA workshops and project Side Event at an ISA Annual Meeting	15+30+40	ISA, GEOMAR
D 4.1	Cruise Reports and meta-data published; photo/video data uploaded to BIIGLE/Vidlib	18 + 36	Cruise chief scientists
D 1.1	Connectivity workshop and report	24	NIOZ
D 6.1	Report about recommended workflow for planning of monitoring of Mn-nodule mining operations	24	GEOMAR
D 8.1	Report on outline of WOE and ENVID model	24	DNV
D 3.2	Interim workshop + report on biogeochemical processes, eco-system functions & data requirements for diagenetic + food-web models	27	CIIMAR & NIOZ
D 2.1	Workshop + report on the fate of trace metals in the plume and modelling of kinetics of trace metal reactions at the sediment-water interface following the deposition of plume material	32	JUB, NTNU
D 1.2	Comprehensive check list for the study area, including data on taxonomy, distribution, biogeography, ecology + life history traits	36	UAveiro
D 6.2	Guidance document on suitability of monitoring technologies	36	JUB & NTNU
D 7.1	Report on ecosystem component responses + sensitivities to pressures, interactions and intensities from mining activities	36	SGN
D 1.3	Report on the usefulness of molecular methods and protocols for biodiversity assessments and environmental monitoring, including metabarcoding, eDNA and ddPCR methods, and proteome fingerprinting for rapid biodiversity assessment	37	SGN
D 2.2	Report on results of numerical simulations of near-field and far-field plume dynamics	38	MARUM, TUDelft
D 2.3	Report on ecological plume impacts and indicator selection integrated in WOE model and quantification of environmental hazards along spatial & temporal plume impact gradients	38	UAlgarve
D 3.3	Data integration & modeling workshop and integrated report on impacts on ecosystem functions	38	GEOMAR & MPI
D 1.4	List of sensitive versus persistent species, report on the analysis of Plenaster as monitoring model species	38	UResearch
D 7.2	Report recommending on scales, indicators + thresholds for EIA	39	UGhent
D 7.3	Report on recolonization by fauna+microbiota, biogeochemistry	41	AWI
D 1.5	Report on connectivity of selected key-species	41	NHM
D 4.2	All project data, specimens, and molecular data are archived for long-term accessibility	43	GEOMAR, SGN, MPI
D 5.3	Publication of final project results in peer-reviewed special issue	43	GEOMAR
D 8.2	Guidance document on methodologies for risk assessment of environmental hazards of deep-sea mining	43	DNV

4. Description of Work Packages and Cross-Cutting Themes

WP 1: Biodiversity, connectivity, resilience

Contributors: UAveiro, IMAR, IFREMER, NHM, NIOZ, MPI, RBINS, SGN, UGhent, ULodz, UNIVPM, UResearch

Goals / Objectives

The primary goal of WP 1 is to understand the regional distribution patterns and biodiversity of biological assemblages, i.e. microbes, meiofauna, macrofauna, and megafauna, and their resilience to disturbances arising from mining operations.

Specific objectives to be addressed are:

- To assess standing stocks, biodiversity a well as taxonomical and trophic composition of the biota in relation to environmental spatial variability
- To increase knowledge on taxonomical and functional biodiversity, biogeography and connectivity by applying integrated molecular and morphological approaches
- To determine biodiversity indicators of "Good Environmental Status" and to assess the short-term impact of an experimental mining created during the nodule collector trial on benthic assemblages as a function of disturbance intensity and habitat variability
- To assess the resilience of biological assemblages and individual species at various spatial and temporal scales
- To develop and test molecular methods and protocols for biodiversity assessment and environmental monitoring

Progress beyond the State-of-the-Art

A) The relevance of molecular approaches for biodiversity and connectivity assessments

Previous work in the CCZ has exposed a highly diverse but almost entirely undescribed fauna. Taxonomic studies have drastically increased the number of known species (Dahlgren et al. 2016, Glover et al. 2016b, Wiklund et al. in press), showing that even relatively limited research effort (i.e. two cruises) may significantly increase the baseline ecosystem knowledge of the region. The first phase of MiningImpact also provided a quality reference database of vouchered and barcoded specimens from the CCZ as well as relevant knowledge on the distribution and connectivity of several common macrofauna species (Glover et al. 2016a, Taboada et al. in press). However, studies addressing connectivity in abyssal areas are almost completely lacking (Taylor and Roterman 2017) and we need better data from REM taxa (i.e. Rare, nodule-Endemic and Megafauna) that represents both the majority of the macrofauna and the vulnerable sessile suspension feeders in nodule areas. Diversity and connectivity assessments based on molecular data depend on taxonomical registers (Sinniger et al. 2016) and are a particularly useful approach for EIAs and monitoring programs in low abundance, but high diversity habitats such as the abyssal plains (Glover et al. 2015). The register of named benthic taxa in the CCZ currently comprises less than 100 species (OBIS 2017). This data shortfall will be addressed by state of the art molecular taxonomy expertise built up from previous work in the CCZ.

Molecular methods have also been used to explore the biodiversity of the oceanic microbiome (e.g., Sogin et al. 2006, Sunagawa et al. 2015, Zinger et al. 2011) including within the deep sea (Ruff et al. 2015, Corinaldesi 2015). The first study to address mining-related impacts on microbial communities, conducted during MiningImpact1, indicated that whilst the removal of the active surface layer of sediment may affect these communities, the effects of the small-scale disturbance in the historical plough tracks are not easy to discriminate from natural variability (Janssen et al. 2017). This calls for an extension of the suite of molecular tools and for studies in more realistic mining scenarios.

Methodological improvements have provided evidence that the large majority of DNA pools in benthic ecosystems is not associated directly with living biomass, but rather to extracellular DNA (eDNA) (Dell'Anno and Danovaro 2005) containing amplifiable prokaryotic and eukaryotic gene sequences suitable for assessing biodiversity at different spatial and temporal scales (Corinaldesi et al. 2008 & 2011). Other molecular methods increasingly used in biodiversity assessments are the metabarcoding and the Maldi-TOF proteome approach (Bik 2012, Laakmann 2013). In the proposed project these three molecular methods will be tested and compared to determine their suitability and/or complementarity as tools for rapid assessments of biodiversity and monitoring of the impact of mining activities on deep-sea microbial an faunal assemblages.

The reference databases built up during MiningImpact1 enable a wide application of metabarcoding and eDNA techniques, revolutionising our ability to undertake biodiversity and connectivity analyses. The new droplet digital PCR (ddPCR) technology (Doi et al. 2015) will be used to develop molecular identification assays for a set of REM taxa, and evaluate their presence and abundance across the CCZ.

B) Innovative approaches for acoustic and image surveys of biological assemblages

Both, image-based and acoustic surveys to assess habitat structure and megafauna community structure have been conducted in polymetallic nodule areas previously, but have seldomly been used to monitor a disturbance event (Bluhm 2001, Greinert 2015, Boetius 2015, Purser et al. 2016, Vanreusel et al. 2016). In this project a range of acoustic and imaging static, towed and autonomous free swimming devices will be used to map at high resolution habitat features and faunal distributions across the surveyed region prior, during and post disturbance. Data collected will be processed using workflows developed during MiningImpact 1 (Marcon and Purser 2016, Dreutter 2017, Purser et al. in press).

C) *Benthic assemblages and spatial heterogeneity*

An overaching goal of WP1 is to describe and understand the spatial and temporal dynamics of benthic assemblages in the CCZ in order to be able to predict the ecological consequences of nodule mining. Spatial heterogeneity is known to influence the structure and composition of benthic communities, as well as the rate of deposition of sinking particulate organic matter in abyssal plains (Morris et al. 2016). In the CCZ, there is increasing evidence that at the local scale, nodules influence the structure and composition of both, infaunal (Miljutina et al. 2010) and epifaunal communities (Vanreusel et al. 2016). At the larger scale, gradients in primary productivity across the CCZ are also known to structure benthic communities (Wedding et al. 2013, Vanreusel et al. 2016). The influence of topography (Gould et al. 1981, Turnewitsch et al. 2013 & 2015), however, has rarely been specifically addressed but is of critical importance for the impact and environmental management of nodule mining. This raises subsequent issues to be explored during MiningImpact2, such as the identification of topography-related patterns of particle deposition and how they may impact specific faunas. The magnitude of impacts varies widely with the scale and intensity of disturbances (Jones et al. 2017) and may last for decades (Miljutin et al. 2011, Vanreusel et al. 2016). The species' potential to recover after major disturbances depends on substrate availability and are strongly linked to specific dispersal strategies and demographic connectivity (Gollner et al. 2015 & 2016). MiningImpact2 will focus on the immediate and short-term response of benthic organisms that is crucial for the recovery of benthic standing stocks and biodiversity, as well as for the maintenance of associated ecosystem functions.

Work Program

WP1 will focus on taxonomic and functional biodiversity, connectivity and resilience of benthic communities and will address both, natural variability and effects of impacts connected to the nodule collector trial. Studies on benthic assemblages (microbiome, meiofauna, macrofauna and megafauna) will follow a Before-After Control Impact (BACI) design with replication conducted during both the baseline study and the impact study in stations located in the areas defined in the general environmental management and monitoring plan (EMMP; see CCT3). The sampling of habitat types and impact levels will be harmonized with the other WPs and CCTs. The exact location of impacted sites for faunal sampling (using e.g. boxcorer, multicorer, EBS, ROV, faunal traps), combined optical and hydroacoustic surveys (with e.g. ROV, AUV, OFOBS), and time-lapse camera deployments will be identified based on impact monitoring carried out in WP2 and CCT1 during and immediately after the collector trial. Results obtained on changes in presence, activity and functions of specific groups of faunal and microbial communities and any impact indicator taxa that can be identified will feed into joint analysis of disturbance effects carried out in CCT2. Particular emphasis will be on the analysis of similarities in the response of different faunal components (meio- macro and megafauna) and microbial communities to specific impact types and intensities and to effects on biogeochemical processes (connection to WP3). This knowledge will help to assess the suitability of biodiversity and community structure analyses of the different faunal compartments and microbial assemblages for future impact monitoring and feed into risk assessment and recommendations addressed in CCT3.

Task 1.1 Megafauna communities and their connection to physical habitat characteristics addressing natural variabilities, disturbance effects, and their temporal evolution (MPI, IMAR)

At each station, detailed seafloor imaging and acoustic data will be collected via AUV, ROV and towed camera platform OFOBS to characterize habitat features and the megafauna communities present at time of survey. Each station will be visited prior and post collector test to allow any changes in megafauna community structure to be identified. Where possible, time-lapse camera units will be deployed on the seafloor prior to the collector trial to observe any visual responses of epifauna to the disturbance.

ROV transects will be conducted at each station before and after the nodule collector trial to collect image data which can be used to assess the plume impact on detritivores, suspension feeders and filter feeders. Once the plume has settled, one transect is to be carried out along the direction of the created plume. A second and a third transect will be carried out at different angles from the same starting point, to analyse different degrees of disturbance regime and to evaluate possible fleeing movements of mobile fauna. These transects will be repeated several times following the collector test, allowing both temporal and spatial responses to be gauged. From the ROV image data, a selection of three key representative megafauna taxa (a suspension feeder, a detritivore and a filter feeder) will be chosen for direct physical sampling. The ROV will then be used to collect representatives of the three taxa to assess their ecophysiology (see WP2).

Task 1.2 Meio- and macrofaunal assemblages and their connection to physical habitat characteristics addressing natural variabilities, disturbance effects, and their temporal evolution (UAveiro, IFREMER, UGhent, RBINS, SGN, UResearch, NHM, ULodz, NIOZ)

This task aims to decipher the spatio-temporal dynamics of the meiofauna and macrofauna from quantitative samples obtained according to the plan introduced above. Onboard sampling of faunal specimens for taxonomic work (morphological and molecular) will follow

Glover et al. (2015) methodology. A combined morphological and molecular approach will be used whenever possible allowing accurate taxonomic identifications, the detection of cryptic diversity and description of new faunal species. Typically invertebrate markers such as cytochrome oxidase I mitochondrial gene (COI), 16S mitochondrial ribosomal RNA coding genes and 18S or 28S nuclear genes will be targeted. This work will extend the existing datsets and will be crucial for further assessments of biodiversity and connectivity.

Taxonomic and trophic diversity and community structure (e.g. alpha and beta-diversity) will be analysed in each faunal compartment and compared between faunal compartments. Functional and trophic relationships within meiofauna and macrofauna assemblages will be explored (e.g. by stable isotope analysis). A metagenomic approach will be used for biodiversity assessments and comparative analyses of selected taxa (e.g. nematode, polychaete and amphipod assemblages). Spatial and temporal patterns of faunal assemblages will be analysed (e.g. multivariate analyses) in relation to comparable data obtained during MiningImpact1 and available environmental parameters (input from WP2 and WP3) and will allow to establish criteria for the definition of “good environmental status”. Sensitive versus persistent species after mining plumes will be identified and listed.

The sponge *Plenaster craigi*, one of the common filter feeders at nodules and likely susceptible to increased turbidity and nodule removal (Lim et al. 2017), is a potential indicator species for mining plume impact. The mapping of *Plenaster craigi* abundance will be carried out using data from box cores and high-resolution in-situ photography and the impact *i* from exposure to experimental sediment plumes will be subsequently assessed.

Short-term impacts of the disturbance experiment on connectivity will be investigated by assessing the dispersal of larvae and resuspended benthos by the disturbance plume (e.g. via resuspended sediment, passive dispersal via currents). The data will be obtained from samples collected by WP2.

Newly obtained molecular data will be used to complement previous and/or ongoing analyses of data from MiningImpact1 and other projects (Glover et al. 2016, Dahlgren et al. 2016, Wiklund et al. in press) and detect shared species within sites of the CCZ. Novel Next-Generation RAD-seq techniques (Burford-Reiskind et al. 2016) will be applied to investigate the population genomics of amphipod species and provide data on population histories and connectivity at high resolution and statistical confidence. Genetic connectivity of mobile and sessile species will be analyzed and related to their recovery potential in the disturbed area and on restoration substrates (see CCT2). Population genomics can allow the detection of Single Nulceotide Polymorphisms (SNP) under selection. We can use these SNP data to unravel species-specific adaptations to deep-sea environments and obtain new data on their resilience.

Task 1.3 Effects of sediment disturbance on microbial and microeukariote communities (MPI, UNIVPM)

Molecular approaches will be applied to sediment samples collected with ROV pushcores prior to and after the collector trial to characterize the microbial and microeukariote communities within undisturbed, directly ploughed and plume exposed seafloor areas.

Microbial community composition and diversity (via 16S rRNA gene Tag sequencing), functional diversity (via metagenomes), and dominant active microbial taxa (via 16S rRNA/cDNA Tag sequencing and metatranscriptomes) will be identified. Analyses will address microbial biodiversity at taxonomic levels ranging from phyla to individual ‘species’ (i.e. operational taxonomic units), as well as links of key-ecosystem functions to specific groups. Investigations of sediments from undisturbed sites will assess regional variability of microbial biodiversity and spatial connectivity while samples from the second leg of the cruise will focus on mining-related effects on communities and functions. MPI will further analyse manganese nodule material focusing on the contribution of communities of the outer nodule layer to the overall taxonomic diversity found in the area. The analyses will further allow for comparisons to communities colonizing the different substrates deployed by CCT2 to assess early stages of recolonization and feed into project partner's work on metal cycling.

Following the same sampling strategy used for microbial assemblages, changes in benthic microeukaryote biodiversity (i.e. protists and fungi) will be investigated through a metagenomic approach applied on extracellular DNA. The extracellular DNA will be selectively extracted from the sediments using a combination of physical and chemical procedures (Corinaldesi et al. 2005, Danovaro 2010), which allow excluding the contamination by the DNA of any biological component, including viruses. Once extracted the extracellular DNA will be amplified by using primer sets targeting 18S rRNA genes and ITS (internal transcribed spacer) of eukaryotes and the amplicons analyzed by high-throughput sequencing platforms (e.g. Illumina MiSeq).

Task 1.4 Development of molecular methods and protocols for rapid biodiversity assessments and environmental monitoring (UResearch, NHM, SGN, UGhent)

A set of ddPCR assays will be developed to target REM indicator species based on the existent reference dataset (Glover et al. 2016, Dahlgren et al. 2016, Wiklund et al. in press). eDNA samples of mud and bottom water will be collected at different stations and exctracted onboard (Lekang et al. 2015). Initial assay feasability tests will be done on CCZ samples readily available and optimal standardized method protocols for use of eDNA and ddPCR in environmental monitoring will be developed.

Sediments will be sampled and fixed for molecular studies prior and after disturbance in the areas influenced by plume deposition as well as not-impacted reference areas, and three different molecular methods for rapid biodiversity assessment will be applied. Ground truthing will be performed by comparing with results generated in WP2 (tasks 2.2 and 2.3). Changes in the pristine abyssal eDNA signature will be investigated following the nodule collector trial and subsequent recovery through time. For the metabarcoding approach, organisms will be extracted from the sediment first and the DNA will be extracted from the whole community without further sorting. Different gene fragments (COI-mini, 18s V1-V2, V4 and V9 regions) will be amplified and sequenced in parallel using Illumina NGS technology and compared to a genetic library for the assignment of taxonomic entities. The suitability of the different gene regions to capture abyssal meiofauna diversity and structure will be examined. For the proteome approach, the whole proteome from single specimens will be measured using Maldi-ToF (matrix-assisted laser-desorption/ionization time-of-flight) mass spectrometry that generates a species-specific fingerprint of the proteins' mass. The aim of this study is to test the efficiency and sensitivity of the three different molecular approaches to detect and monitor changes produced by mining impacts and recovery through time of the standing stocks and community structure in micro, meio and macrofaunal communities.

Work Schedule

	2018		2019				2020				2021				2022
	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1
Cruise preparation & participation	X	X	X	X											
1.1 Megafaunal assemblages															
3D acoustic data processing			X	X	X	X	X	X	X	X	X	X	X	X	
Annotation, analyses, publication			X	X	X	X	X	X	X	X	X	X	X	X	X
1.2 Macro- & meiofaunal assemblages															
Sample sorting			X	X	X	X	X	X							
Molecular work			X	X	X	X	X	X	X	X					

Species ID, taxonomy, publication					X	X	X	X	X	X	X	X	X	X	
Connectivity analyses, publication							X	X	X	X	X	X	X	X	
Biodiversity analyses, publication							X	X	X	X	X	X	X	X	
1.3 Microbiome & microeukariota															
DNA/RNA extraction, sequencing						X	X	X	X	X					
Bioinformatic analyses, publication								X	X	X	X	X	X	X	X
1.4 Development of molecular tools			X	X	X	X	X	X	X	X	X	X	X	X	
Data integration & interpretation															
Spatial patterns, heterogeneity													X	X	X
Recovery, indicator species													X	X	X
Scientific valorization													X	X	X

Milestones / Deliverables

M 1.1 Sampling and survey activities completed and metadata supplied to data archive (month 12, IMAR)

M 1.2 Sequencing and imaging data submitted to public data archives and shared among project participants (month 28, UAveiro)

M 1.3 Benthic assemblage biodiversity data across size classes disseminated to CCT2 for integrated analysis (month 36, UGhent)

D 1.1 Connectivity workshop and report (month 24, NIOZ),

D 1.2 Comprehensive check list for the study area, including data on taxonomy, distribution, biogeography, ecologyand life history traits (month 36, UAveiro),

D 1.3 Report on the usefulness of molecular methods and protocols for biodiversity assessments and environmental monitoring, including metabarcoding, eDNA and ddPCR methods, and proteome fingerprinting for rapid biodiversity assessment (month 37, SGN)

D 1.4 List of sensitive versus persistent species, report on the analysis of *Plenaster* as monitoring model species (month 38 UResearch; with contributions from WP2 and CCT2)

D 1.5 Report on connectivity of selected key-species (month 41, NHM)

WP 2: Fate & toxicity of the sediment plume

Contributors: NIOZ, UAlgarve, MARUM, JUB, AWI, GEOMAR, MPI, BGR, CIIMAR, IPMA, RBINS, NIVA, NTNU, UDelft, IMAR, USOU, UGhent, UUtrecht

Goals / Objectives

- Monitoring of sediment plume dispersal, plume sediment redeposition, and numerical modelling of near-field and far-field plume dynamics including particle aggregation processes
- Characterization of the physical and chemical properties of the plume in space and time using both, field data and ex-situ experiments (particle aggregation processes and fate, trace metal dynamics)
- Spatial and temporal quantification of the ecological effects of the sediment plume on benthic and planktonic fauna: tolerance to increased suspended particle concentration, physiological and ecotoxicological effects (e.g. bioaccumulation, biomarkers, toxicity bioassays), epigenetic alterations, shifts in coral and deep-water microbial assemblages, reproductive aspects and larvae viability

Progress beyond the State-of-the-Art

Current knowledge on sediment mobilization and dispersal induced by deep-sea mining is based on benthic impact experiments carried out more than two decades ago. In these experiments the extent of redeposited sediment in the surroundings of the impacted sites was inferred from seabed imagery (Yamazaki et al. 1997) and from numerical simulations forced by time-series measurements of ocean bottom currents and imposed static particle sizes and settling velocities (e.g., Nakata et al. 1997, Jankowski and Zielke 2001, Rolinski et al. 2001). Deep-sea observational technology at the time of those experiments did not allow for comprehensive monitoring of the actual sediment plumes as they were spreading laterally and vertically away from the source site, nor could particle aggregation processes which critically determine the redeposition of sediments from the plume be assessed. Similarly, our understanding of the impact of mining plumes on the deep-sea environment is not based on direct observation, but inferred from ecological status assessments before and after impact experiments, *ex-situ* sediment exposure and ecotoxicological experiments conducted with model species from shallower-water depths, and observations made in shallow-water settings.

Taking advantage of the DEME nodule collector trials in the CCZ, which is expected to generate a plume of substantial size and persistence, and building forth on experience gained in the first project phase in the application of a range of state of the art deep-sea sensor technology, instrument platforms, *in-situ* experimental techniques, automated image analysis, etc., MiningImpact2 will substantially advance insights into the mining plume dynamics and environmental impacts. A 3D array of optical and acoustic turbidity sensors and particle cameras on static and mobile platforms will be implemented to monitor the experimental plume (see CCT1). In addition, alternative methods for assessing bottom water turbidity, and automated analysis of seabed images (Schoening et al. 2017) will be applied to investigate the extent of the plume-impacted seafloor area (Peukert et al. in prep) and to extrapolate coverage of nodules with resettled plume particles (Alevizos et al. in prep).

With the currently available computational power it is now possible to numerically simulate the dynamic initial stage of plume formation. This initial stage, in which momentum of the turbulent water flow generated by the nodule collector prevails over background current dynamics, is strongly determining the further evolution of the plume in the far field. Particle aggregation processes, not taken into account in previous modeling of mining induced plumes, can now be specifically implemented in the updated regional ocean circulation-sediment transport model developed for simulating far-field plume dispersal as part of the work proposed here. This modeling effort will be supported by *in-situ* observation and *ex-situ* experiments addressing turbulence-induced particle aggregation in the bottom boundary layer as well as scavenging of particles by seasonal phytodetritus falls.

From previous lab experiments it appears that especially the resuspension of the manganese-oxide rich surface sediment layer may lead to a very strong sorption of trace metals in the water column and metal release at oxic conditions is rather unlikely for most metals (Koschinsky et al. 2003). However, nothing is currently known about the potential role of microbial interactions within plume particles and redeposited sediments that may affect the mobility and flux of metals, changes in oxidation states of metal ions and organic-metal complexation. Sensitivity of deep-sea holothurians to enhanced concentrations of trace metals has been demonstrated by *in-situ* enclosure experiments (MIDAS, 2016, Brown et al. 2017). Potential mobilization of trace metals in sediment plumes and redeposited sediments will be addressed by geochemical analysis of bottom water and surface sediment samples, shipboard and laboratory experiments, and numerical modeling of trace metal reactions.

MiningImpact2 will investigate the different impacts that mining plumes may have on deep-sea biota, such as translocation of benthic microbial communities and small meiobenthos from the mined area where the plume is generated to the area of redeposition of plume material, physical damage inflicted by suspended sediment particles on meroplankton and zooplankton living in the near-bottom water, impaired feeding and respiration in filter feeding and suspension feeding megabenthos like corals and sponges due to sediment clogging, and ecotoxicological effects due to metal containing particles and dissolved metal (cooperation with WP3). Much of this work will be conducted for the first time, not only for this part of the Pacific Ocean but for this water depth in general and will be complemented by *in-situ* and *ex-situ* sediment exposure studies. Variable responses by deep-water corals and sponges exposed to various types of particulate matter have been observed: (a) high survival and minor sub-lethal effects in the scleractinian coral *Lophelia pertusa* (Larsson and Purser 2011, Larsson et al. 2013, Allers et al. 2013); (b) reduction in metabolic rates, deteriorating tissue condition, tissue necrosis and death in the octocoral *Dentomuricea meteor* (Carreiro-Silva et al. in prep); (c) high tolerance to sedimentation with reduced metabolic activity in the sponge *Geodia baretti* (Kutti et al. 2015). The potential role of microbial symbionts in deep-water corals will also be assessed as recent studies suggest that microbial symbionts may enhance resilience of coral hosts (e.g., Yakimov et al. 2006, Kellogg et al. 2009, Middelburg et al. 2015, Kellogg et al. 2016).

The environmental hazard by the plume will be evaluated by means of the quantitative weight of evidence (WOE) model, in which impact on biota and ecosystem functioning is assessed with information from the chemistry (in the different environmental matrices) and from the ecotoxicological impact (integrating data from bioavailability, bioaccumulation, biomarker responses, and toxicity bioassays on bioindicator species; Viarengo et al. 2007). This WOE model has already been validated to classify environmental hazards in different environmental settings characterized by greater complexity of contaminant mixtures, origin, typology and intensity of pollution (Piva et al. 2011, Bebianno et al. 2015, Mestre et al. 2017).

Work Program

WP2 focuses on assessing the fate and impact of the sediment plume generated by the nodule collector trials performed in the German and Belgian contract areas in the CCZ. The work will involve monitoring of the dispersal of suspended sediment and sediment redeposition in space and time, assessment of the evolution of physical (e.g., particle concentration, size, and aggregation) and chemical (e.g., trace metals) characteristics of the plume as it is drifting away from the site of its origin, and assessment of the impact of the sediment plume on seafloor sediment and biota (in cooperation with WP1 and WP3).

Field observations and experimental work will generally follow the EMMP-based experimental strategy developed in CCT1. Baseline investigations of bottom water, surface sediments, nodules, and biota will be collected in collaboration with other WPs during the first leg of the SONNE cruise (scheduled for early 2019) from sites where the major plume impact is expected to occur, as well as from unimpacted reference sites. An array of plume monitoring platforms with different sensors will be deployed along the anticipated main direction of plume dispersal, prior to the onset of the nodule collector trial and it will remain in place until the start of the second leg of the cruise. Sampling and experimental work will focus on establishing spatial and temporal trends in plume characteristics and immediate plume impacts. The below description of WP2 tasks focuses on investigations carried out during the two legs of the core research cruise, scheduled for February to May 2019 on RV SONNE. If additional ship-time can be made available within the lifetime of the project, WP2 partners are interested to extend their investigations within the limits of the available funding, to assess plume impacts on longer time scales.

Plume monitoring data and experimental results will be used for calibration and validation of near-field and far-field sediment transport models which are an important tool for predicting the areal extent of sediment dispersal resulting from industrial mining operations. Results from *in-situ* and *ex-situ* geochemical and biological experiments will be integrated with diagenetic and food web modeling carried out in WP3 to improve predictions of mining impacts on the deep-sea ecosystem. Knowledge obtained on the suitability of instruments and methods for monitoring and evaluating mining impact will be integrated in method assessments in CCT1 and provided to CCT3 to feed into the development of policy recommendations. The work of WP2 is organized in the three interconnected tasks.

Task 2.1 Plume dispersal and sediment deposition (GEOMAR, BGR, NIOZ, RBINS, MARUM, UDelft, NTNU, JUB, AWI)

This task addresses the dispersal of suspended material in the sediment plume in space and time and the spatial extent and amount of sediment redeposition from the plume.

Following the experimental design developed in CCT1, a 3D sensor array will be geared up by joint effort of **GEOMAR**, **BGR**, **NIOZ** and **RBINS** and deployed on moorings and landers across the areas designated for the nodule collector field trials in the German and Belgisn contract areas. Apart from standard oceanographic sensors, the array will include a large number of acoustic and optical turbidity sensors with different sensitivity and measuring range, as well as particle cameras, to monitor the lateral and vertical dispersal of the plume and evolution of its physical characteristics as it drifts away from its site of origin. **BGR** will focus on long-term (seasonal) variability of currents and rates of sediment deposition, and to that end deploy current profiler and sediment trap moorings already on a cruise in April 2018. During the SONNE cruise monitoring the nodule collector trial the traps will be redeployed close to the seafloor at a proximal and a more distal position downstream of the mining test site, in concert with traps deployed by **GEOMAR** and **NIOZ**, in order to record particle fluxes settling from the plume within certain proximities to the test site. **RBINS**, **JUB**, and **GEOMAR** will focus on particle aggregation in the bottom boundary layer, assessed *in-situ* by particle cameras, in relation to suspended particulate matter concentration determined by different types of turbidity sensors and turbulence determined from high-frequency ADV current measurements.

In addition to the static sensor array, **GEOMAR** will deploy its AUV and ROV for dynamic monitoring of the plume. Next to optical turbidity sensors, multibeam WCI technology and ADCP-backscatter on the ROV will be used to track the sediment plume in real-time allowing for an adaptive monitoring (real time data access via the ROV). Likewise, the AUV will be used to record turbidity along predefined vertical and lateral transects through the plume, using standard optical turbidity sensors as well as haze analysis of photos taken with HD camera along the transects. Data processing will be conducted directly on board to adapt the monitoring scheme if necessary and to support targeted sampling for sedimentological, geochemical and biological studies (WP1 and 3). To assess net deposition of sediment from the plume, **GEOMAR** will employ automated image analysis on photomosaics collected by AUV prior, during and after the disturbance experiment, as well as advanced AUV-based multibeam backscatter analysis to quantify extent and thickness of sediment blanketing. Resettled sediment thickness will also be constrained by placing checker boards with ruler-sticks in the anticipated impact area to be photographed by ROV and AUV. These image-based analyses will be compared with results from sediment physical and radionuclide analyses of sediment cores by **AWI**, **GEOMAR**, and **NIOZ**.

NTNU plans to add fluorescent tracer material to the sediment plume generated by the nodule collector by means of a diffusor. The environmentally friendly tracers are anticpated to disperse with the sediment plume and care will be taken to fabricate tracer particles that closely mimic the plume particle properties with respect to sinking velocity and hydrodynamics. Experiments in this regards will be conducted prior to the collector trial in cooperation with DEME and JUB. The tracer itself can be detected up to several years after deployment and thus also allows tracing of secondary suspension and redeposition. A rapid evaluation can be done already onboard applying fluorescence microscopy.

Modifying numerical models developed for shallow-water dredging plumes, and using turbidity sensor data from the direct vicinity of the collector test area for validation and calibration, **UDelft** will perform model simulations of the initial stages of the plume in the near-field of the nodule collector. Results from the comprehensive plume monitoring program and from experiments addressing sediment particle properties and ensuing evolution of the sediment concentration and sediment deposition will enable **MARUM** to calibrate and test the new flocculation module integrated in the numerical regional ocean circulation-sediment transport model which was developed during MiningImpact1. The complete set of *in-situ*/*ex-situ* experiments will allow for adapting the flocculation model of Winterwerp (1998) for the deep-sea environment and provide a suitable flocculation parameterization applicable to other deep-ocean environments.

Task 2.2 Evolution of physical and chemical characteristics of the plume (JUB, AWI, NIOZ, NTNU)

This task will address the physical and chemical characteristics of the plume as well as the temporal and spatial evolution thereof.

JUB will carry out laboratory experiments, if possible onboard the SONNE cruises, focusing on aggregation and hydrodynamic behaviour of particles in the plume. Experiments will be conducted under *in-situ* temperature and salinity conditions with sediments from the CCZ, using shear tanks, roller tanks and benthic resuspension chambers. Using different particle concentrations and turbulence regimes, optimal conditions for aggregate formation and thereby enhanced redeposition of plume particles will be determined. This may provide guidance for engineering solutions and operational practices that help to reduce plumes formed in the wake of mining operations. In addition, the effect of seasonal phytodetritus falls on the removal and redeposition of fine-grained suspended sediment from the plume will be determined using isolated microalgae from the CCZ cultivated onboard, and with particle concentrations of 175-2000 mg L^{-1} (as also used for discharge models of drill cuttings in the oil & gas business by Norwegian authorities).

Potential mobilisation of trace metals in the plume and their bioavailability will be addressed by **JUB** in collaboration with **AWI**, **NIOZ** and **NTNU**. Samples of plume particles and surrounding plume water in spatial and temporal gradients from/after the disturbance event, collected by means of CTD/Niskin and ROV, will be analysed for major and trace element composition as well as natural radionuclide concentrations. Laboratory experiments will be set up to study the sorption-desorption and dissolution-precipitation equilibria between plume particles and bottom water under defined conditions, e.g. under variable redox conditions, particle density, type and size of suspended particles. Of particular interest is the role of microbial interactions with plume particles on trace metal reactions, e.g. the role of heavy-metal resistant bacteria, the role of particle aggregation in the plume on the trace metal distributions, and the distribution of trace metals between different physical and chemical species and the role of colloids in transporting trace metals in the water column. **NTNU** will develop a numerical model of trace metal reaction kinetics, using published data on reaction kinetics and integrating empirical results from the experiments conducted by **JUB**. On the basis of the model, potentially toxic metal fluxes induced by mining activities may be predicted.

Task 2.3 Ecological impact of the plume (UAlgarve, IPMA, IMAR, CIIMAR, NIVA, UGhent, RBINS, USOU, UUtrecht, SGN, JUB, MPI)

This task assesses the impact of the sediment plume and sediment deposition on biota, and integrates all impact data into a weight-of-evidence (WOE) model to classify environmental hazard.

Bottom water, sediments, nodules, and organisms will be collected during this task, using CTD, multicorer, boxcorer, SyPRID and ROV, from the same sites before and after plume impact as well as an intermediate time during the collector trial. Environmental parameters, such as temperature, pH, and O_2, will be assessed in collaboration with WP3 and CCT1. **UAlgarve** will evaluate the toxicity of the resuspension plume against the natural background toxicity established for the studied areas. Toxicity bioassays will be looking at different endpoints (e.g. survival, reproduction, larval development) with different organisms (Bebianno et al. 2015, Simpson et al. 2016) such as *V. fischeri* bacterium, amphipods and/or bivalves. Results will be compared with those previously obtained for sediment and nodules from the German contract area, thus providing an overview of natural toxicity levels of the region. Samples of sediment and nodules to be used in bioassays will be analysed for grain size, bulk chemical composition and organic matter content by **UAlgarve** and **IPMA** in collaboration with **AWI**, **GEOMAR** and **JUB** in WP3. Collected specimens of representative faunal groups will be analysed by **UAlgarve** for metal contents and for baseline biomarker levels indicative of oxidative stress, metal exposure, biotransformation, oxidative damage, and neurotoxicity (Mestre et al. 2017). In addition, the bioconcentration factor of legacy contaminants (PCBs, PBDEs, organochlorine pesticides; extendable to PAHs and non-targeted screening) in both, amphipods (Lysianassidae) and the sediment plume, using techniques outlined in Jamieson et al. (2017) will be analysed by **RBINS**. Metal contents, changes in molecular signaling pathways, epigenetic regulation and gene expression will be evaluated by **IPMA**, **IMAR** and **CIIMAR** before as well as during plume generation.

UAlgarve and **IMAR** will analyse collected Anthozoans from areas exposed to the plume to assess the response of the coral host to sedimentation. Anatomy and changes in the gonodal tissue within the mesoglea will be investigated by optical and electron microscopy (Waller and Baco 2007, Hall-Spencer et al. 2007). In addition, the microbiome response to increased sedimentation will be assessed, using high-throughput 16S rRNA gene next-generation sequencing and transcriptomics (Hall-Spencer et al. 2007, Lawler et al. 2016) in order to describe (a) taxonomically or functionally conserved bacterial associates of the selected species and (b) shifts in anthozoan microbiome composition and function in response to increased sediment load. Collected corals will also be subjected to condition index analyses, energy budget analysis (proteins, lipids, carbohydrates), and biomass measurements. **IMAR** and **JUB** will further conduct *ex-situ* controlled aquarium experiments to test the impact of different concentrations of CCZ sediments with and without POC using cold-water corals from the Azores region. Eco-physiological responses in aquaria will be compared with *in-situ* octocoral reponses to better understand the interaction between sediments and POC and determine sediment concentration thresholds on the physiology of these organisms.

NIVA, in collaboration with **UAlgarve** and **SGN**, will use the WHOI SyPRID plankton sampler (Billings et al. 2017) adapted to the ROV to collect meroplankton (e.g. larvae) and zooplankton (e.g. copepods) inside and outside of the plume. SyPRID is a novel sampling equipment that allows obtaining paired, large-volume plankton samples of well-preserved specimens at specified depths. Optical and electron microscopic analyses will allow assessment of physical damage of body parts, entanglement of particles on swimming structures, inclusion of particles in stomach contents, damage of feeding structures (mouth parts) and organs. These results in combination with those obtained in WP1 will represent the first data on larvae of CCZ communities. Provided enough material is collected, the metal accumulation and biomarker levels will also be assessed in collaboration with **UAlgarve**. In collaboration with **UGhent**, the SyPRID samples will also be used to assess presence of resuspended benthic meiofauna in the plume. Changes in microbial community composition, functions and metabolic activities that occur when sediments are translocated within the plume will be studied by **MPI**, mainly as a contribution to WP1 and WP3. The primary interest of these investigations is to follow the fate of resuspended organisms and the functions that they provide from source to sink, but data may also allow addressing effects of the resuspended matter and contaminants on the native microbial communities in bottom waters.

CIIMAR, **UUtrecht**, **USOU** and **UAlgarve** will investigate short-term effects of exposure to sediment plumes in deposit-feeding megafauna (e.g., holothurians), using benthic corrals (Brown et al. 2017) that will be deployed *in-situ* over targeted specimens by ROV. Filter/deposit-feeder organisms and other components of the benthic community (prokaryotes, meio- and macrofauna) will be sampled close to the corral deployment locations before disturbance and within corrals after disturbance for analysis of bioaccumulation, biomarkers and guided de novo transcriptomes. In another *in-situ* experiment, **CIIMAR** and **UUtrecht** will investigate physiological responses of filter feeders exposed to sediment plumes within CUBE benthic incubation chambers (slightly modified with respect to Stratmann et al., in prep). The CUBEs will be placed by ROV over specimens of common filter-feeding species before and after disturbance, followed by respiration measurements and water sampled at pre-set time steps to detect changes in nutrient fluxes from which changes in uptake or excretion by the organism can be assessed.

UAlgarve will classify environmental hazard at each sample location, including sites exposed to the plume, with the elaboration of a quantitative weight-of-evidence (WOE) model (e.g. Bebianno et al. 2015, Mestre et al. 2017) that integrates data from different levels-of-evidence (LOE), such as sediment/plume chemistry, bioaccumulation/bioavailability, sub-lethal effects/biomarkers, bioassay results. The WOE model will be applied to different sampling times, i.e. before impact, shortly after impact, and if additional ship-time can be made available, also 1-2 years after the impact, in order to provide insight into the temporal evolution of plume impact hazards. WOE results will contribute to CCT3.

Work Schedule

	2018		2019				2020				2021				2022
	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1
2.1 Plume dispersal and sediment deposition															
2.1.1 Monitoring of plume dispersal	Instrum. prep., instr. Deploym.					Data analysis input to 2.1.3					Integration with 2.1.2, publication				
2.1.2 Sediment deposition from the plume	Cruise prep., sampling					Sample/data anal., input to 2.1.3					Integration with 2.1.1, publication				
2.1.3 Numerical modeling of near-field and far-field plume dynamics	Cruise operational model					Calib./valid./impl flocculation model					Apply model scenarios, publication				
2.2 Evolution of physical and chemical characteristics of the plume															
2.2.1 Particle aggregation	Cruise prep., sampling					Sample/data anal., input 2.1.3					Integration with 2.2.2, publication				
2.2.2 Trace metal dynamics	Cruise prep., sampling					Sample/data anal., input 2.3.1					Integration with 2.2.1 & 2.3, publication				

2.3 Ecological impact of the plume			
2.3.1 Physical, biogeochemical, ecotoxico-logical impacts on benthic/planktonic fauna	Cruise prepar. sampling	Sample/experiment/data anal., input 2.3.2	Integration with 2.2.2 & 2.3.2 publication
2.3.2 WOE evaluation			Integration with 2.1, 2.2 & 2.3.1, publication

Milestones / Deliverables

M 2.1 Plume monitoring, sampling and experiments successfully conducted during SONNE cruise (month 9, NIOZ)

M 2.2 Setup of numerical models for near-field and far-field plume dispersion (month 15, MARUM & TUDelft)

M 2.3 Data from plume monitoring array, seabed image analysis, plume particle dynamics and plume trace metal reactions processed and ready for integration in plume dispersal and geochemical models (month 24, GEOMAR & JUB)

M 2.4 Workshop on the spatial and temporal ecological effects of the plume to identify suitable impact indicators (month 24, UAlgarve)

D 2.1 Workshop and report on the fate of trace metals in the plume and modelling of kinetics of trace metal reactions at the sediment-water interface following the deposition of plume material (month 32, JUB & NTNU)

D 2.2 Report on results of numerical simulations of near-field and far-field plume dynamics (month 38, MARUM & TUDelft)

D 2.3 Report on ecological plume impacts and indicator selection integrated in WOE model and quantification of environmental hazards along spatial & temporal plume impact gradients (month 38, UAlgarve)

WP 3: Biogeochemistry and ecosystem functioning

Contributors: MPI, CIIMAR, AWI, GEOMAR, JUB, MARUM, NIOZ, UUtrecht, UGhent, UNIVPM

Goals / Objectives

- Identification of the local spatial variability of sediment physical characteristics and biogeochemical processes in the study area
- Quantification of the changes induced by the collector trial with respect to the spatial extent of direct (e.g., surface sediment and nodule removal, sediment compaction, porewater release) and indirect mining impacts (sediment blanketing) on physical sediment properties (e.g., shear strength, water content), redox zonation, diagenetic fluxes (e.g., oxygen, nutrients, Mn, Fe, trace metals) and biogeochemical processes including particulate and dissolved organic matter degradation and trace metal reactions
- Effects of mining activities on microbial ecology and functions with a focus on organic matter remineralization, productivity, and mortality (microbiological and molecular tools, tracer incubations)
- Effects of suspended and resettled sediment plumes and differences in nodule coverage on organic matter remineralization by benthic communities, including microorganisms, meio-, macro- and megafauna (in situ experiments and food web models)

Progress beyond the State-of-the-Art

Biogeochemical processes in deep-sea sediments are nowadays recognized as key functions of abyssal ecosystems playing a significant role in large-scale element fluxes with consequences for, e.g., the productivity of the seas (via nutrient regeneration) and for the global carbon dioxide budget (via organic matter remineralization and burial) (e.g., Sweetman et al. 2017). Sediment biogeochemistry of undisturbed ecosystems is shaped by complex interactions of chemical and microbially-controlled processes and benthic food webs. This, in turn makes organic matter fluxes from the overlying water available to benthic communities, sustaining their biomass and unprecedented biodiversity.

Most experiments addressing environmental impacts of deep-sea mining were carried out several decades ago (e.g., Thiel and Schriever 1992) and missed out on the effects on biogeochemical processes. First field investigations on biogeochemical alterations did not start before the late 1990s, i.e. several years after the disturbances were created (e.g., Haeckel et al. 2001). Modern instrumentation (e.g., ROV-targeted sampling and in situ sensors) needed for precise characterization of the nature and intensity of impacts and fully controlled investigations and sampling to address their biogeochemical consequences were not available at that time. Other recent methodological advances, e.g. molecular tools for the characterization of microbial communities (e.g., DeLong 2005), pulse-chase experiments to quantify transfer of energy and matter in benthic food webs (e.g., Witte et al. 2003), and advanced technologies for in situ measurements of benthic fluxes (e.g., Boetius and Wenzhöfer 2009) have added further important tools for studying deep-sea biogeochemistry.

Investigations carried out in the first project phase, particularly in the DISCOL Experimental Area (DEA), successfully addressed mining-related effects on benthic biogeochemistry with a comprehensive suite of state of the art technologies (Boetius 2015, Martínez-Arbizu and Haeckel 2015). For the first time, these investigations could provide direct evidence for impacts on seafloor biogeochemical processes several decades after the disturbances were created (Vonnahme et al. in prep.). Investigations have also shown that even after a few decades, the geochemical composition and redox layering of surface sediments in nodule areas is still strongly altered by the disturbance, while pore waters seem to equilibrate much quicker (Paul et al. submitted). At the same time, many biogeochemical parameters showed an unexpectedly high spatial variability suggesting the need to thoroughly characterize baseline conditions, in order to identify mining-related effects and to assess their significance in comparison to naturally occurring variations (Mewes et al. 2014, Mogollón et al. 2016, Volz et al. in prep., Vonnahme et al. in prep.). These investigations also documented that biogeochemical effects are specific to the particular nature and intensity of the physical impact with the strongest effects observed, where active surface sediments with labile organic matter were lost and deeper sediment layers got exposed at the surface. These stiffer and less porous sediments seem harder to recolonize by bioturbating organisms that mix in fresh organic matter and created favorable conditions for re-establishing stable biogeochemical conditions and processes.

Activities of organic-matter degrading enzymes, oxygen consumption rates, organic matter quality, porosity, and radioistopes constraining bioturbation activity proved, in the first project phase, to be very effective monitoring variables for assessing the overall status of benthic biogeochemical functions (Vonnahme et al. in prep). However, in order to conduct comprehensive numerical simulations of effects on biogeochemical functions and food webs, including prognostic modeling of their expected recovery, as proposed here, an even more comprehensive suite of biogeochemical variables is needed. This will result in an extensive dataset that will allow to characterize the physical impact and to quantify biogeochemical process rates and will include, e.g., in situ studies of sediment geomechanical properties and benthic fluxes, radionuclide and stable isotope studies, food web experiments directly at the seafloor, and investigations of microbial and viral productivity and functions. As investigations will address freshly created impacts by a heavy collector system that probably involves significant sediment compaction and porewater expulsion, investigation will allow addressing effects that occur on shorter temporal scales and better represent realistic scenarios compared to studies in decade-old disturbances created with relatively small and lightweight gear. Furthermore, the larger disturbance area of the collector trial will, for the first time, allow for representative investigations of secondary disturbance effects (i.e., sediment blanketing by resettling plume material) while precluding apparent recovery of biogeochemical conditions by lateral processes (e.g., diffusion and recolonization) from areas in the direct vicinity of the disturbance tracks. Studies on the natural heterogeneity and on the effects of different impact types and intensities on biogeochemical processes and overall benthic ecosystem functions will be captured and harmonized with investigations carried out in WP1 and 2 by adoption of the monitoring scheme developed in CCT1.

Work Program

WP3 aims to assess mining impacts on seafloor ecosystems with a focus on sediment physical characteristics (e.g., shear strength, porosity, diffusivity), and respective effects on sediment biogeochemical characteristics, processes and fluxes (e.g., regarding oxygen, nutrients, organic matter, metals) as well as ecosystem functions (e.g., organic matter remineralization, food webs). Natural heterogeneity is addressed as well as effects of direct (e.g., compaction, sediment and nodule removal) and indirect disturbance (sediment blanketing) following the EMMP-based experimental strategy developed in CCT1.

Baseline investigations, particularly filling the gaps in the existing data of the collector trial area, are carried out during the first leg of the cruise. Effects of the impacts created by the collector are studied directly after the disturbance during the second leg of the cruise to assess severity and spatial extent of immediate effects and to establish a starting point for investigations of longer-term changes (secondary effects and recovery) during anticipated post impact expeditions. Ex situ analyses, shipboard incubations and shore-lab experiments using sediment samples obtained by ROV pushcoring and deployments of video-guided multicorer, gravity corer, and boxcorer are combined with in situ measurements and dedicated experiments performed directly at the seafloor. The below description of WP3 tasks focuses on investigations carried out during the two legs of the core research cruise, scheduled with RV SONNE for February to May 2019. If additional ship-time can be made available within the lifetime of the project, all WP3 partners are prepared to continue their investigations during a reconnaissance cruise within the limits of the available funding.

The findings are integrated by diagenetic and food web modeling and correlated with habitat and plume mapping carried out in WP2 and CCT1 to quantify the overall consequences and predict impacts of full scale industrial mining operations (CCT2). Knowledge obtained on the applicability of state of the art instruments and methods and the relevance of the obtained data to assess mining effects on seafloor ecosystems are fed back into CCT1 for integration and uptake in recommendations developed in CCT3. The work is organized in five interconnected tasks:

Task 3.1 Effects on sediment physical properties and porewater expulsion (GEOMAR, JUB, AWI)

This task assesses the physical impact associated with the collector test and its effect on key sediment properties, such as shear strength, compaction/porosity, and diffusivity.

To investigate the mechanical response of the sediment to test mining in terms of compaction and porewater expulsion, **GEOMAR** will assess geomechanical properties of the surface sediments before and after the collector trial by means of the 'GraviProbe', an innovative geotechnical device provided by DEME-GSR for in situ analyses of the top 4 m of sediment. By a combination of an accelerometer with a pressure sensor, natural variability and changes in static bearing strength of the sediments will be determined and compared to shear strength measurements performed in **GEOMAR**'s high-pressure experiment lab (Deusner et al. 2016) as part of this project as well as to past investigations in different nodule areas. In cooperation with **GEOMAR**, **JUB** will investigate the impact of sediment compaction by the collector on porosity and the effect of the reduced pore space on diffusion and sorption/desorption properties. Investigations will focus on trace metal behaviour and will include measurements of porosity and trace metal distribution in multicores and pushcores as well as experiments on trace metal diffusion in sediment slides of different porosity. **AWI** will study natural radium, thorium, and actinium radioisotopes in samples obtained with bottom water samplers and in situ pumps to quantify the loss of pore water (as well as particles; see WP2) from the sediments upon disturbance by the collector. Data on sediment properties and impact related changes will feed into diagenetic modeling (Task 3.3).

Task 3.2 Assessment of sedimentation and bioturbation dynamics (AWI, NIOZ, GEOMAR, MARUM)

This task addresses sedimentation rates and bioturbation characteristics (depth, rate) as key factors of natural sediment deposition and reworking and key input parameters for diagenetic modeling (Task 3.3). Natural variabilities are addressed as well as effects of impacts to quantify changes and to serve as starting point for subsequent assessments of recovery.

AWI, **GEOMAR** and **NIOZ** will analyze vertical distributions of natural and anthropogenic radionuclides in sediments from multicores and pushcores to assess rates of sediment accumulation and bioturbation as well as the depth of the bioturbated layer. In cores from disturbed sites, this will further allow to quantify the layers of sediment lost by disturbance or deposited from settling plumes. Studies focusing on different radionuclides in sediment solids and pore waters with different chemical properties and half lives carried out by **AWI** (^{226}Ra, ratios of ^{230}Th/^{231}Pa, ^{234}U/^{238}U) and **NIOZ** (^{210}Pb, ^{137}Cs) will be combined to address processes associated with different sediment compounds and different time scales. The studies will be complemented by high resolution 3D X-ray imaging (Computed Tomography, CT) by **MARUM** of intact cores sampled nearby. This will allow to visualize and quantify structures indicative of disturbance effects (exposed dense subsurface sediments, blanketing with unconsolidated plume sediments, cracks, buried nodule debris) and biogenic activity (macrofauna burrows). CT analyses will be compared to geochemical and radionuclide data of **NIOZ, AWI** and **GEOMAR** and validated with radionuclide analyses performed on samples from specific structures in selected cores.

Task 3.3 Effects on sediment biogeochemistry (redox zonation, diagenetic fluxes, biogeochemical processes) (GEOMAR, AWI, JUB, MPI, CIIMAR, UNIVPM)

This task quantifies the degree of changes in sediment biogeochemical characteristics and diagenetic processes and fluxes and their footprints in comparison to natural variability observed at undisturbed sites. Investigations will be based on a comprehensive dataset of biogeochemical process variables comprised of dissolved porewater and solid phase constituents and key isotopic signatures measured on sediment core samples collected by means of multicores, pushcores, and gravity cores and will be complemented by in situ respiration measurements.

GEOMAR will carry out extensive geochemical analyses of porewaters and solids including nutrients, the carbonate system, dissolved metals, major cations, sulfate and total sulfur, and isotopic ratios, e.g., of C, H, O, Sr, and Li). The focus of **AWI** will be on the effects of sediment and nodule removal on porewater distributions of oxygen, and nutrients, and on different Fe and Mn mineral phases. Fe and Mn reactivity will be addressed by sequential extraction and analyses of stable Fe isotopes. **JUB** will mainly dedicate its analyses on the effects of sediment compaction on the redox zonation and the distribution of elements with special emphasis on trace metals, their dynamic biogeochemical reactions. This also includes investigation of N-isotopes and organic compounds (DOC, amino acids) indicative of organic matter degradation processes. **UNIVPM** will apply spectrophotometric/fluorometric methods to quantify organic compounds (e.g., phytopigments, proteins, carbohydrates, lipids as well as extracellular DNA concentrations), assess their bioavailability and contribution to phosphorous cycling as well as respective changes in response to the collector impact. Additional measurements will be carried out by **CIIMAR** (HPLC-based characterization of phytopigments) and **MPI** (fluorometric quantification of Chl*a* and phaeopigments in selected cores). Data on sediment biogeochemistry changes will feed into the experiments (Task 3.5) and biogeochemical model simulations.

MPI will complement sample-based investigations by in situ quantifications of diffusive and total benthic solute fluxes (primarily oxygen) to assess respiration rates as a proxy for microbial activity and organic matter remineralization. Investigations will be carried out in situ at the seafloor with automated microprofilers and benthic chambers deployed with MPI’s autonomous lander platforms or as self-contained modules manipulated by ROV.

GEOMAR will employ state-of-the-art numerical diagenetic modelling to analyze the data in combination with information on sediment physical characteristics as well as sediment deposition and reworking provided by Tasks 3.1 and 3.2. This will allow quantifying processes and fluxes in order to identify key effects on biogeochemical ecosystem function and to predict the time scales required to relax back into steady state. Subsequently, the geochemical data collected at discrete sites and corresponding model-derived rates and fluxes will be correlated with spatial information from habitat and plume mapping, conducted in WP2 and CCT1, to estimate the overall change caused during the collector trial.

Task 3.4 Effects on microbial ecology and functions (MPI, UNIVPM)

This task assesses ecosystem functions of microbial communities as key components of benthic ecosystems in terms of biomass and their contribution to biogeochemical processes. By a combination of molecular and microscopic methods with shipboard tracer incubations, key functions of microbial communities and viruses are identified and quantified. Information on microbial functions is subsequently analyzed in combination with data on biogeochemical processes (Task 3.3).

MPI will quantify microbial activity and biomass production (via ^{3}H-labeled leucine and ^{14}C bicarbonate) in undisturbed and impacted sediments. Additional measurements in ground nodule material will address the activity of nodule-specific microbial communities. Microbial activities will further be quantified (in terms of radiotracer incorporation and extracellular enzymatic activity) in samples taken in mining plumes to investigate the effects on functions of microorganisms relocated from pristine surface sediments as well as of natural bathypelagic microbial communities. Rate measurements in sediments will be accompanied by microscopic quantifications of microbial abundance and biomass. In addition, MPI will combine molecular techniques for the quantification of microorganisms with measurements of radiotracer uptake into microbial cells to assess the contribution of specific functional groups to overall microbial biomass production.

Using sediments sampled in impacted and reference sites, **UNIVPM** will carry out shipboard incubations with fluorescent analogues of organic substrates to determine potential activities of the main extracellular enzymes as a proxy of the degradation potential of organic matter by prokaryotes. UNIVPM will further assess effects on virus productivity and virus induced prokaryotic mortality. While production will be determined based on the increase in viral abundance in incubations of diluted sediments, epifluorescence and transmission electron microscopy will be used to quantify virus-induced prokaryotic mortality.

Task 3.5 Effects on ecosystem functioning (CIIMAR, NIOZ, UGhent, UNIVPM)

This task assesses mining impacts on benthic ecosystem functioning at the abyssal seafloor by in situ experiments and food web modeling with a focus on effects of the settling and re-suspension of plume material on organic matter processing. The experimental work is carried out directly at the seafloor using open (**USOU** 'Corrals') and sealed benthic enclosures (**NIOZ** 'CUBES') that are deployed by ROV. All experiments follow the pulse-chase approach where labelled particulate organic material (^{13}C and ^{15}N algae 'POM') or dissolved organic material (^{13}C labelled and ^{15}N 'DOM') is added to the enclosures. This will be used to assess the transfer of matter and energy in the benthic food webs by taxa of all size classes with special emphasis on surface deposit-, and filter-feeding megafauna that are expected to be particularly affected by sediment blanketing and suspended matter loads. The analysis of the samples extends beyond WP3 and involves ecotoxicological / transcriptome studies carried out by **UAlgarve** and **CIIMAR** in WP2. Natural C and N stable isotope signatures of all the benthic assemblages will be quantified by means of isotope ratio mass spectrometry in background samples taken close to the experiment sites. In addition the freshness of sedimentary organic matter will be determined at the experiment sites (**UNIVPM** and **CIIMAR**, see also Task 3.3).

CIIMAR, **NIOZ**, and **USOU** will deploy Corrals before the collector trial along the predicted gradient of plume material settling to investigate immediate effects of mining-induced sedimentation on organic matter utilization of the benthic food webs with a focus on holothurians as key deposit-feeding megafauna organisms (*Experiment 1*). The uptake of ^{13}C and ^{15}N labelled POM added to the corrals will be quantified in holothurians and all other benthic organisms collected from the corrals (**CIIMAR**, **NIOZ**, **UGhent**).

After the collector test, **NIOZ**, and **CIIMAR** will deploy CUBEs over sessile encrusting or stalked sponges and control areas without sponges that have been exposed to different amounts of resettled plume material. ^{13}C and ^{15}N labelled DOM will be added to address the effects on the uptake of DOM and the metabolic activity of sponges and other members of the benthic community (*Experiment 2*). In addition to quantifications of uptake of labeled DOM by the microbial, meio-, macro- and megafaunal assemblages (**NIOZ**), total oxygen uptake will be determined by continuous oxygen monitoring in the overlaying water and discrete samples for the determination of nutrient fluxes will be taken throughout the deployment.

NIOZ and **CIIMAR** will carry out additional deployments of CUBEs over sponges and sponge-free control areas that were subject to thick plume sediment blanketing to assess the effect of re-suspended plume material on the physiology of sponges (*Experiment 3*). In contrast to Experiment 2, clouds of suspended sediment will be created in the CUBEs by means of intense stirring or sediment injection. Changes in oxygen and nutrient fluxes will be determined throughout the incubation. Remineralization of added labelled DOM and the alteration of its composition will be determined by ^{13}C-DIC measurements and fluorometric FDOM scanning in water samples. Additionally, the uptake of labelled DOM will be quantified in sponges and all other benthic organisms collected from the CUBEs (**CIIMAR**, **NIOZ**, **UGhent**).

NIOZ will combine results from the experiments with benthic biomass estimates (input from WP1) and assessments of organic matter freshness and biogeochemical process rates (Task 3.3) for model-based food web analyses. Linear inverse food web models that proved successful to assess disturbance effects in the DEA in the first project phase (Stratmann et al. in prep.) will be employed with a focus on the effects of difference in nodule coverage and organic matter availability.

Work Schedule

<table>
<tr><th rowspan="2"></th><th colspan="2">2018</th><th colspan="4">2019</th><th colspan="4">2020</th><th colspan="4">2021</th><th>2022</th></tr>
<tr><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th><th>1</th><th>2</th><th>3</th><th>4</th><th>1</th></tr>
<tr><td colspan="16">3.1 Effects on sediment physical properties, pore water & particle release</td></tr>
<tr><td>3.1.1 Assessing sediment geomechanics</td><td colspan="5">Instrum. prep., instr. Deploym.</td><td colspan="5">Data analysis input to 3.3.4</td><td colspan="5">Integration with 3.1.2, publication</td></tr>
<tr><td>3.1.2 Impacts on porosity, diffusive properties, pore water & particle release</td><td colspan="5">Cruise prep., sampling</td><td colspan="5">Sample/data anal., input 3.3.4</td><td colspan="5">Integration with 3.1.1, publication</td></tr>
<tr><td colspan="16">3.2 Assessment of sedimentation & bioturbation dynamics</td></tr>
<tr><td>3.2.1 Assessment of sedimentation & bioturbation activity with radioisotopes</td><td colspan="5">Cruise preparat., sampling</td><td colspan="5">Sample/data anal., input 3.3.4</td><td colspan="5">Integration with 3.2.2, publication</td></tr>
<tr><td>3.2.2 3D X-ray investigations of sediment physical & biogenic properties</td><td colspan="5">Cruise prep., sampling</td><td colspan="5">Sample/data anal., input 3.3.4</td><td colspan="5">Integration with 3.2.1, publication</td></tr>
<tr><td colspan="16">3.3 Effects on sediment biogeochemistry</td></tr>
<tr><td>3.3.1 Sample-based characterization of sediment solid-phase & pore waters</td><td colspan="5">Cruise prepar. samplg.&analys.</td><td colspan="5">Dat. anal., input to 3.3.4&3.5.2</td><td colspan="5">Integration w. 3.3.2 & 3.4.1, publication</td></tr>
<tr><td>3.3.2 In situ quantification of O_2 fluxes</td><td colspan="5">Instrum. prep., instr. deploym.</td><td colspan="5">Dat. anal., input to 3.3.4&3.5.2</td><td colspan="5">Integration w. 3.3.1 & 3.4.1, publication</td></tr>
<tr><td>3.3.3 Organic matter characterization</td><td colspan="5">Cruise prep., sampling</td><td colspan="5">Samp/data anal. Inp. 3.3.4&3.5.2</td><td colspan="5">Integration w. 3.3.1 & 2, 3.2.1, publicat.</td></tr>
<tr><td>3.3.4 Impact simulations and prognostics with numerical diagenetic modelling</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="4">model setup, data collec.</td><td colspan="3">model runs, validat., pub.</td></tr>
<tr><td colspan="16">3.4 Effects on microbial ecology and functions</td></tr>
<tr><td>3.4.1 Rates of organic matter decomposition, microbial & viral productivity</td><td colspan="5">Cruise preparat., sampl.&incubat.</td><td colspan="5">Dat. anal., input to 3.3.4&3.5.3</td><td colspan="5">Integration w. 3.4.2, 3.3.1&2, publication</td></tr>
<tr><td>3.4.2 Microbial functions & virus-induced mortality</td><td colspan="5">Cruise preparat., sampl.&incubat.</td><td colspan="5">Sequenc.,sampl. & data analysis inp. 3.3.4&3.5.2</td><td colspan="5">Integration w. 3.4.1, 3.3.1&2, publication</td></tr>
<tr><td colspan="16">3.5 Effects on ecosystem functioning</td></tr>
<tr><td>3.5.1 Food web experiments</td><td colspan="5">Cruise preparat., sampl.&incubat.</td><td colspan="5">Samp./dat. anal. input 3.5.2</td><td colspan="5">Integration with WP2, publication</td></tr>
<tr><td>3.5.2 Food web models</td><td></td><td></td><td></td><td></td><td></td><td colspan="5">Food web model development</td><td colspan="5">model runs, validation, publication</td></tr>
</table>

Milestones / Deliverables

M 3.1 Sampling, *in situ* measurements and experiments conducted successfully during baseline and impact cruise (month 9, MPI)

M 3.2 Biogeochemical sediment characteristics, fluxes, and organic matter processing by benthic communities (including baseline variability and effects of impacts) quantified, presented at annual meeting, and provided to project partners for integration in CCT2 (month 27, CIIMAR & MPI)

M 3.3 Setup of food-web and diagenetic models and first simulations results discussed with project partners (month 39, NIOZ & GEOMAR)

D 3.1 First results and data from field work, in situ and experimental studies are made available to project partners (month 12, MPI)

D 3.2 Interim workshop & report on biogeochemical processes, ecosystem functions, and data requirements for diagenetic and food-web models (month 27, CIIMAR & NIOZ)

D 3.3 Data integration & modeling workshop and integrated report on impacts on ecosystem functions (month 38, GEOMAR & MPI)

WP 4: Data & sample management

Contributors: GEOMAR, MPI, SGN, UBielefeld, MARUM

Goals / Objectives

This work package will:

- organize long-term storage of the generated data and collected samples
- facilitate sharing of data and knowledge between project partners as well as distribution of sample material to partners not able to join the cruises
- develop and implement new video annotation and geospatial browsing capabilities for the BIIGLE 2.0 software
- develop and implement a central global BIIGLE server to improve collaboration support and knowledge exchange

Progress beyond the State-of-the-Art

While the main task of this work package is to organize and facilitate archival of the generated data and samples in databases with established structures and capabilities, such as PANGAEA and European museum collections, a second objective is to further develop the capabilities of the BIIGLE 2.0 image annotation software. In the context of the proposed project we expect an increasing demand for sharing of knowledge and image data between partners, such as morphotype catalogues in WP1, annotating videos and integrating geospational information or maps with annotation results (e.g. species abundances). To meet these demands we propose to extend the BIIGLE 2.0 functionalites in this regard.

The field of computational marine image analysis is rather new. The ultimate dream of a fully generalizable automated marine image annotation seems rather unreachable due to the strong variation in imaging conditions, huge species' diversity and low per-species density, especially in the context of this project and the results of the first project phase. To make manual annotation by visual inspection of experts more efficient, different tools have been proposed in the last years, such as SQUIDLE, CATAMI, PAPARAZZI, ECOTAXA, and BIIGLE. Although these systems provide valuable support for the annotation process the integration of all the data (annotation, taxonomic catalogues, etc) across many institutes has not been addressed enough so far. This can lead to undesired annoyances for users changing sites and projects and redundancies so this problem must be addressed now.

Only a very few annotation systems have been proposed for video annotation (e.g. VIDLIB, Adelie) although the analysis of video data collected with ROV is one standard procedure in marine biology, environmental sciences or underwater infrastructure inspection. One special problem seems to be the lack of a clear general problem specification, like a definition of a labeling protocol and how to avoid a time consuming labeling of objects in multiple consecutive frames. It seems obvious, that this task could benefit from an integration of algorithmic solutions like machine learning to make video annotation more efficient.

In the first phase of MiningImpact the focus was put on the development of DIAS, a first alpha-version of a mobile software for the annotation of marine image collections recorded with different platforms such as AUV, ROV or OFOS during the three expeditions in 2015. After the cruises the DIAS system was merged with the already existing BIIGLE (Benthic Image Indexing, Graphical Labeling and Exploration) database to a new online annotation database system BIIGLE 2.0 (Langenkämper et al. 2017) and used for annotation in the acquired image data.

In the proposed project MiningImpact 2, the aim is to address image analysis issues in a practical mining monitoring context and to develop methods for problems related to temporal mining impact monitoring and posterior observation. In all phases of mining we can expect that images with a variety of platforms will be collected, such as OFOS (Ocean Floor Observation System), AUV (Autonomous Underwater Vehicle), ROV (Remote Operating Vehicles) but in the context of this project video data will play a role of greater significance as well as the evaluation of (time lapse) image sequences from camera-equipped underwater observatories (FUO) or landers. This large amount of accumulating image and video data (with some images covering a visual footprint of approx. 400 m^2 per image) needs to be evaluated regarding impact assessment such as sediment plume patterns or habitat information, such as nodule abundance and associated fauna. A large amount of this image and video evaluation is done by human observers who shall jointly annotate regions of interest with pre-defined semantic categories, morphologies or taxonomies and integrate the annotation results with geospatial information. To support users in this task BIIGLE 2.0 will be extended with new functions not offered by other platforms.

Work Program

WP4 will provide effective management and archiving of the collected samples and generated data (as already executed in the first project phase), based on established protocols and best practices for research expeditions, the specific code of conduct for marine sciences, and the EU principles of data and knowledge sharing. The work program is divided into three main tasks, the data management, the sample management, and internal knowledge transfer and exchange. Data management will cover all types of data generated during the cruises and post-cruise in the participant's laboratories. Sample management will deal with all aspect of sampling with the devices deployed at sea and their appropriate conservation for transport and storage. Post-cruise, WP workshops and annual meetings will ensure the exchange of knowledge between the project partners.

Task 4.1 Data Management

As in the first project phase, MiningImpact 2 will generate huge volumes of data across all work packages and scientific disciplines. These comprise of a large variety of different data types, such as acoustic data from e.g. multibeam and side-scan sonars and Acoustic Doppler Current Profilers (ADCP), photo and video images from AUV, ROV and towed camera surveys, comprehensive concentration datasets of a multitude of chemical compounds in the water column and the sediment, faunal diversity and abundances, genetic information and microbial parameters.

This task will cover the entire life cycle of the obtained project data from recording, processing, consistency and technical quality assessment, to archiving. Directly after the SONNE cruise, the ship's station list and all metadata from sampling and observations as well as raw and processed hydroacoustic data will be stored in the MaNIDA data base, which is accessible also from the EMODnet data portals. **GEOMAR** will facilitate the long-term storage of the project data in the information system PANGAEA at the World Data Center for Marine Environmental Sciences (WDC-MARE) through its Ocean Science Information System (OSIS-Kiel). OSIS-Kiel will also be used for sharing of datasets among project partners. PANGAEA is operated on a long-term basis by **AWI** and **MARUM**. All data will be geo- and time-referenced and deposited with a Digital Object Identifier (DOI) to make them citable and retrievable by library catalogues or Google Scholar. Data published within PANGAEA are provided through harvesting techniques for global distribution. These techniques include standard metadata exchange formats as ISO19115, Dublin-Core, and OAI-PMH. Two further features of PANGAEA are geo-referencing of data and establishing best-practice guidelines to allow efficient browsing in spatially and temporally organized data.

A project data policy will be generated to specify time schedules from data creation to internal project availability and final publication (time periods will be adjusted according to the scientific disciplines) in PANGAEA as well as general data use agreements. These data sharing modalities will achieve a stable research support environment for all project partners and will guarantee the availability of the project data to the scientific community beyond the project's life time.

All molecular data concerning fauna will be deposited in GenBank, overseen by **SGN**. **MPI** will take care of the storage of microbial samples and will upload all sequencing data with the appropriate sets of metadata via GFBio to the European Nucleotide Archive (ENA) and PANGAEA. **MPI** will further upload all image and hydroacoustic OFOBS survey data to PANGAEA. Video data collected with OFOBS as well as other video-footage provided by project partners will be uploaded to the video annotation platform vidlib (http://vidlib.marum.de) for joint analysis by project members. This may be extended to other video-footage provided by project partners if needed, e.g. for comparison with the video annotation functionality added by **UBielefeld** to BIIGLE 2.0 (Task 4.3).

Task 4.2 Sample Management

The distribution of samples taken for fauna will be coordinated by the German Center for Marine Biodiversity Research at partner **SGN**. After the life time of the project, participants will be asked to return any non-needed samples and biological material to **SGN** for long-term storage. Holotypes of new species will be deposited in an appropriate collection of a European natural history museum (e.g. Natural History Museum in London, Muséum National D'Histoire Naturelle in Paris, Senckenberg in Frankfurt) and information on the fate of samples and specimens will be made available to **SGN**. Sediment and porewater samples from collected cores will be stored in the **GEOMAR** core repository. WP4 will also organize onboard sampling for partners who are not able to join the SONNE cruise.

Task 4.3 Video Annotation Software BIIGLE

UBielefeld proposes to develop the algorithmic basics and software structures for an advanced marine image analysis toolbox BIIGLE 2.0 that allows users to perform the image and video analysis necessary for environmental monitoring in polymetallic nodule mining. The research is separated into the following subtasks.

a) Video Annotation: Based on the experiences and basic database structures **UBielefeld** will develop video annotation capabilities for the BIIGLE 2.0 tool (Langenkämper et al. 2017), which are currently limited to still images only. Since the necessity for video annotation was expected quite early, the underlying database structure (developed in the first project phase) already considers video data and data derived from videos. To develop the video annotation tool, a number of studies with experienced users from marine biology will be carried out to carefully render the specifications for the tool. This includes data specification (e.g. volumes, codecs, etc) as well as usability issues. In addition to the software development itself, general guidelines for video annotation will be set up, similar to those outlined for still images in the first project phase.

b) Data integration and fusion: In addition to the BIIGLE 2.0 system installed at partner institutes **GEOMAR**, **SGN** and **UBielefeld**, the *mobile* BIIGLE 2.0 system will be used during cruises at sea. To support a flexible use not only of the image data but also of derived data, such as label trees and morphotype catalogues, all of these data need to be hosted by a global data server together with user ID and user information. It should be noted that such a server is not intended to become a new data repository itself (as these already exist, e.g. PANGAEA). The aim is to support collaboration and standardization in annotation and to avoid redundancies at the local BIIGLE spots.

During mining operations the annotations and statistics of the objects and events in the images and videos must be analyzed in a geospatial and temporal context. Thus, we will also implement new interfaces and routines that support a data fusion in the geospatial and / or temporal domain. These new integrated data sets enable users to browse and analyze the data from different perspectives which is necessary to work on different scales in time (short/long term impact) or space.

c) Geospatial browsing support (for mosaics and bathymetric maps): To link the annotation results to geographical information, a more sophisticated tool for geospatial visualization, browsing and filtering will be implemented. Currently, BIIGLE 2.0 visualizes the locations of the images using *OpenStreetmap*. Users can visualize images (e.g. selected according to a species abundance filter) at a geographical location or select images according to their geographical location for a detailed visualized inspection. The new module shall support users to plot this information on imported bathymetric maps or other kinds of maps. If video data is provided with geospatial information, geospatial gating or filtering through the map will be supported as well.

Work Schedule

	2018		2019				2020				2021				2022
	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1
Data & Sample Management															
Cruise data stored in databases					X	X					X	X			
Post-cruise data to PANGAEA							X	X	X	X	X	X	X	X	X
Sample requests (prior to cruises)	X	X							X	X					
Fauna / microbe / DNA sample archival											X	X	X	X	X
Video Annotation Software BIIGLE															
Development of video annotation tool			X	X	X	X	X	X	X	X					
Data integration and fusion											X	X	X	X	X
Geospatial browsing support	X	X													

Milestones / Deliverables

M 4.1 Data policy, including schedule for data sharing, archival, and open access, is agreed on by all partners (month 3; GEOMAR)

M 4.2 Shared datasets are made available to all project partners via OSIS-Kiel, PANGAEA, BIIGLE, Vidlib and internal project website (month 15; GEOMAR)

M 4.3 Geospatial browsing and video annotation tool have been tested successfully (month 24; UBielefeld)

D 4.1 Cruise Reports and meta-data published; photo/video data uploaded to BIIGLE/Vidlib (month 18 + 36; chief scientists of SONNE cruise)

D 4.2 All project data, specimens, and molecular data are archived for long-term accessibility (month 43; GEOMAR, SGN, MPI)

WP 5: Project dissemination & coordination

Contributors: GEOMAR, GRIDA, ISA

Goals / Objectives

Building on the experiences and the established contact network of the first project phase WP 5 will:

- organize workshops with policymakers, NGOs, ISA contractors and interested industry as well as countries planning offshore mining operations in their EEZ to communicate project results and discuss implications
- communicate the project results to inform the public about the topic of deep-sea mining
- organize sessions on deep-sea mining at international scientific conferences, such as EGU, Goldschmidt, AGU, UMC.

Work Program

Task 5.1: Dissemination Activities

In order to achieve effective dissemination of the project outcomes, **GRIDA** will perform an audience analysis that will lead to an updated compilation of the existing stakeholder database. Dissemination and outreach will be carried out both in a passive (making information available) and an active (targeted events) way. Part of the outreach efforts will be devoted to disseminate to a high-level audience (e.g. decision-makers).

a) Workshops and Conferences: Project partner **ISA** will organize targeted workshops on specific topics, such as spatial management, risk assessment, monitoring plans and technology, and environmental impacts. These are aimed at discussing and exchanging knowledge with ISA's contractors, policymakers, NGOs, interested deep-sea mining industry, as well as countries planning on offshore mining activities in their exclusive economic zones (EEZ). In addition, we plan to organize at least one Side Event at an ISA Annual Meeting in Jamaica to present the project's results and policy recommendations to the ISA Council, LTC, contractors, mining industries, and NGOs.

International conferences, such as UMC, OMS, EGU, AGU, and Goldschmidt, are good opportunities to inform the science community, but also industry and the general public about the project results. **GEOMAR** will initiate the application of special sessions at several conferences during the project's life time.

b) Outreach products: This task will be focused on the production of outreach products that explain deep-sea mining impacts on the environment to both a non-specialized, and a specialized audience, such as policy stakeholders, who are interested in specific aspects of deep-sea mining. The content of these outreach products will be carefully selected so that they match the different purposes and audiences for which they will be produced. The main outreach products will be the specific integrated project results produced in **CCT1**, **CCT2**, and **CCT3**. As part of this task, **GRIDA** will develop a number of policy briefs in order to highlight the major research findings obtained through the project, explore policy options if suitable and provide recommendations on the best options. Supporting science to policy outreach and dissemination could also be served by innovative geospatial products like Story Maps. This will be determined as part of the audience analysis mentioned above,

c) Website: The existing project website, consisting of public and secure internal areas, will be used for external, but also internal communication. The secure internal project website will be used as a vehicle to enhance communication between project partners and facilitate data management in **WP4** by providing entrance to PANGAEA and the OSIS-Kiel data portal.

GRIDA and **GEOMAR** will be responsible for updating and maintenance of the website. These activities include publication of project newsletter, press releases, and social media feeds running throughout the project's lifecycle. Updated information on project progress and developments in research, policy and industry related to deep-sea mining will be further disseminated, including social media activities. A project benchmarking system will be developed by **GRIDA** at the onset of the project and included in the internal protected area of the website to allow for internal monitoring and evaluation of progress (quality, time/cost) in the achievement of the project goals.

Task 5.2: Project coordination and governance

The project coordination at **GEOMAR** will organize annual meetings for all participants to present their results and discuss further joint data analyses and interpretation. As in the first project phase interested stakeholders and policymakers will be invited to these meetings to foster knowledge exchange, but also help the project to focus on relevant issues, e.g. towards policy regulations. Individual WP workshops will be organized by the respective WP leaders. This organization leads to a comprehensive project governance structure (Fig. 5.1) that allows collaborative decision making and consultation within the JPI Oceans framework.

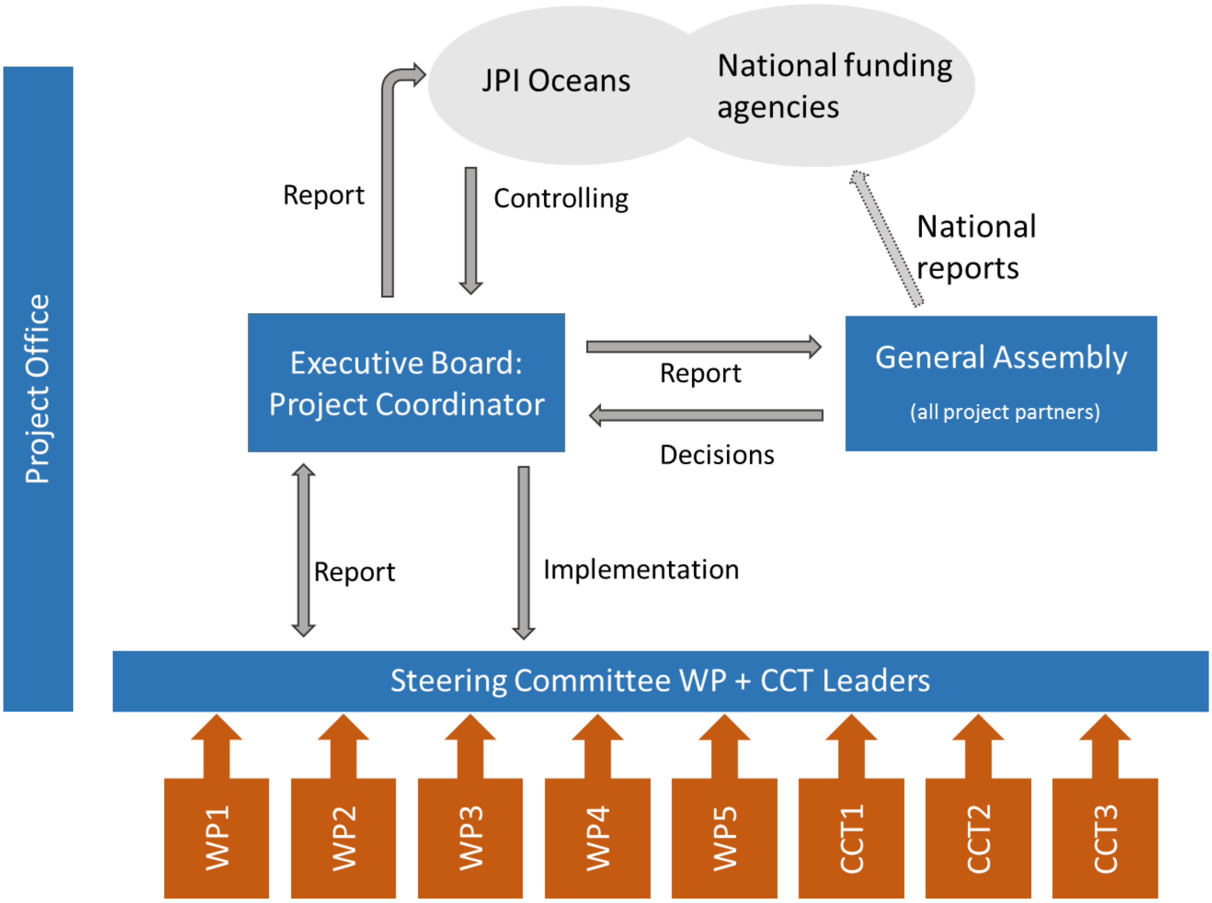


Figure 5.1: Outline of the project governance structure.

In addition, the coordination will organize the joint project reporting to JPIOceans and at the SONNE status seminar. Finally, a special issue publication of the main project results is envisioned in an internationally reviewed scientific journal, ideally with open-access policy, such as Biogeosciences.

Work Schedule

	2018		2019				2020				2021				2022
	3	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**
Workshops + Conferences	X				X			X			X				X
Project Website & Outreach products	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Annual reports and meetings	X				X				X				X		X

Milestones/Deliverables

M 5.1 Regular updates of project website (every 3 months, GRIDA)

M 5.2 Annual project meetings (months 1+13+25+43, GEOMAR)

D 5.1 ISA workshops and project Side Event at an ISA Annual Meeting (months 15+30+40, ISA & GEOMAR)

D 5.2 Publication of focused project reports on WP and CCT topics (month 12+24+36, GRIDA & GEOMAR)

D 5.3 Publication of final project results in an internationally peer-reviewed special issue (month 43, GEOMAR)

CCT 1: Plume monitoring & habitat/disturbance characterization

Contributors: GEOMAR, JUB, AWI, SGN, MPI, BGR, NIOZ, RBINS, NIVA, DNVGL, NTNU

Goals / Objectives

The proposed project MiningImpact2 will investigate the dispersal of mining plumes in great detail, complemented by *in-situ* and *ex-situ* sediment exposure studies. All onsite data will be fed into a near-field plume model which will be used both, for ground truthing of the model and to carry out prognostic plume dispersal simulations under varying hydrodynamic conditions. In this context, CCT1 focuses its efforts on the planning and execution of the monitoring of the sediment plume created by the nodule collector trial, which is a core part of the SONNE cruise. This requires a combination of in-situ real-time measurements with onboard experiments and shore-based numerical sediment plume simulations (WP2) as well as site selection for baseline and impact sampling (WP1 and 3). Thus, CCT1 has the following goals:

- Planning of the SONNE cruise with regards to an EMMP layout: planning of habitat mapping, preparation of the plume monitoring program advised by numerical oceanographic and sediment plume dispersal modelling prior and during the cruise.
- Coordinate and assure instrument calibration of sensors and agreement on joint data processing techniques and best practices
- Undertake pre-impact assessment of the habitat distribution by high resolution mapping (hydroacoustic and optical mapping using AUV and ROV) during the cruise.
- Coordinate the overall in-situ monitoring of the large-scale plume induced by the nodule collector as well as the post-impact assessment
- Coordinate and verify in-situ and ex-situ experiments prior and during the cruise with regards to particle behavior
- Evaluate the usefulness and efficiency of employed monitoring technologies and sensors and provide respective recommendations for best practices

Progress beyond the State-of-the-Art

Operational monitoring of deep-sea mining activities and of the environmental impacts requires an integrated approach. The overall aim is to avoid (or at least minimize) damages to the abyssal ecosystem, particularly sensitive or rare fauna, outside the mined area. Environmental concerns associated with the sediment discharge in the course of deep-sea mining include (a) the burial of benthic organisms by the resettling sediment plume, (b) oxygen depletion in the blanketed seabed and the water body inside the plume through reactive constituents (e.g. labile organic matter or reduced metals), and (c) the release and deposition of toxic metals, which can lead to bioaccumulation of contaminants. The latter is also a well-known problem for the release of oil & gas drill cuttings (e.g., Neff et al. 2000, Breuer et al. 2004, Rye et al. 2007, Rune et al. 2011). Real-time sensor-based monitoring which can be tied closely to monitoring operations is mainly performed with landers, ROVs, and increasingly with AUVs. MiningImpact 2 will apply these technologies as part of its environmental monitoring program around the prototype nodule collector field trial of DEME to provide more realistic information about the environmental footprints and consequences. This is a critical step forward, because upscaling of the “small-scaled” experiments as they have been undertaken in the past, such as the Benthic Impact Experiment II (Brockett and Richards 1994; Tsurusaki 1997), the Japan Deep-Sea Impact Experiment (Barnett and Suzuki 1997), and the IOM-BIE (Kotlinski and Stoyanova 1998; Radziejewska 2002), is very difficult if not impossible.

The methodologies used so far in impact studies are often based on traditional sampling strategies, where data are collected with various sampling platforms (moorings, landers) and sensors giving substantial temporal and spatial gaps. Little emphasis has been given on integration of information between time periods of investigation, thus limiting the possibility to separate the impacts from overall natural variation in an area (Rune et al. 2012). Thus, a primary goal of CCT1 is to provide a guidance document on how monitoring of the seabed around mining operations should be performed. However, lack of standardization of monitoring techniques in accordance with present knowledge and latest advances in technologies precludes comparison of the situation before mining, during mining, and post mining, creating comparable challenges as for deep-water drilling pertains (ANON 2011, Purser and Thomsen 2012). This further demonstrates the need for systematic and scientifically acceptable approaches, the utilization of adequate sampling and observation technologies and the design of monitoring strategies. The most suitable impact assessment of the various impacts on different habitat categories that might be exposed to plume material needs to be supported by adequate sampling. Aside from cost efficient technologies for real-time monitoring of plume dispersion and sediment resettling, the main bathymetric and oceanographic features of the mining site have to be implemented in a predictive dispersion model (e.g., Reed and Rye 2011) that is based on local current information of high temporal resolution (minimum of 12 data points per day) over prolonged time (~1 year) from the vicinity of mining operations. These dispersion models enable evaluating the likely transport pathways of sediments, thereby allowing for a much better positioning of monitoring gear. Particle aggregation processes, not taken into account in previous modeling of mining-induced plumes, should be implemented in updated regional and near-field ocean circulation and sediment transport models. This will be supported by *in-situ* observation and *ex-situ* experiments addressing turbulence-induced particle aggregation in the bottom boundary layer as well as scavenging of particles by seasonal phytodetritus falls (Pabortsava et al. 2011, Thomsen and McCave 2000).

MiningImpact2 will investigate the dispersal of mining plumes in great detail, complemented by *in-situ* and *ex-situ* sediment exposure studies. For the first time, a real-time 'experimental' impact assessment of a nodule collector trial will be conducted. All field data from both in-situ sensors and ex-situ experiments will be transferred onshore to the physical oceanography partners at MARUM to be fed into a near-field plume model which will be used for both, ground truthing of model results and to predict the plume dispersal under varying hydrodynamic conditions, which is needed for adaptive monitoring.

Work Program

Task 6.1: Exchange with DEME on the nodule collector trial

Essential for planning an appropriate experimental layout is a detailed knowledge of the technical specifications of the collector vehicle and its nodule removal and sediment dispersion concept. Technical details, such as the collector size, sediment uptake and dilution, volume flow at the disperser, the vehicle's speed and track, need to be considered. As the experiment will only include testing of the collector system, but does not include nodule transport to the ship, Mn-nodules need to be disposed after a certain amount of time (depending on the amount and size of Mn-nodules on the seabed). In addition, technical adaptations on the collector to carry a particle tracer release box and additional other monitoring equipment need to be defined. The locations of the potential test mining sites (ca. 300 x 300 m^2) need to be defined based on already existing background data. This task will already begin well ahead of the start of MiningImpact 2.

Task 6.2: Planning of the experiment and the SONNE cruise station time

Task 6.2.1 Numerical oceanographic and sediment plume modeling prior the cruise: It has been agreed on to perform the nodule mining experiments in the German and Belgian contract areas. For both areas particle transport modelling will be conducted which includes information on bathymetry, particle properties, aggregation/disaggregation under differing turbulence and sediment loadings, expected blanketing as well as information from existing long-term ADCP deployments. Such data will be provided by DEME and BGR for the respective areas. Model results need to be available for planning the layout of the monitoring array.

Task 6.2.2 Planning of EMMP layout: Based on information from Task 6.1 and 6.2.1, multiple Plume Impact Reference Zones (PIRZs) and Preservation Reference Zones (PRZs) will be defined, while the Impact Reference Zone (IRZ) contains the entire collector trial area. The location of PRZs and PIRZs will be determined based on plume modelling results (Task 6.2.1) and supervised/unsupervised seafloor classification and habitat mapping efforts using ship- and AUV-based bathymetric and optical information as well as geological and biological sediment sampling data during and after the mining activity (WP1, 2, and 3). We aim at covering two or three different habitats with regards to environmental conditions, such as Mn-nodule coverage, geology, and bathymetry, but that exist in each of the defined PIRZs and PRZs. In total, we aim at investigating six to nine areas prior, during and after the collector disturbance (see WP1 to 3).

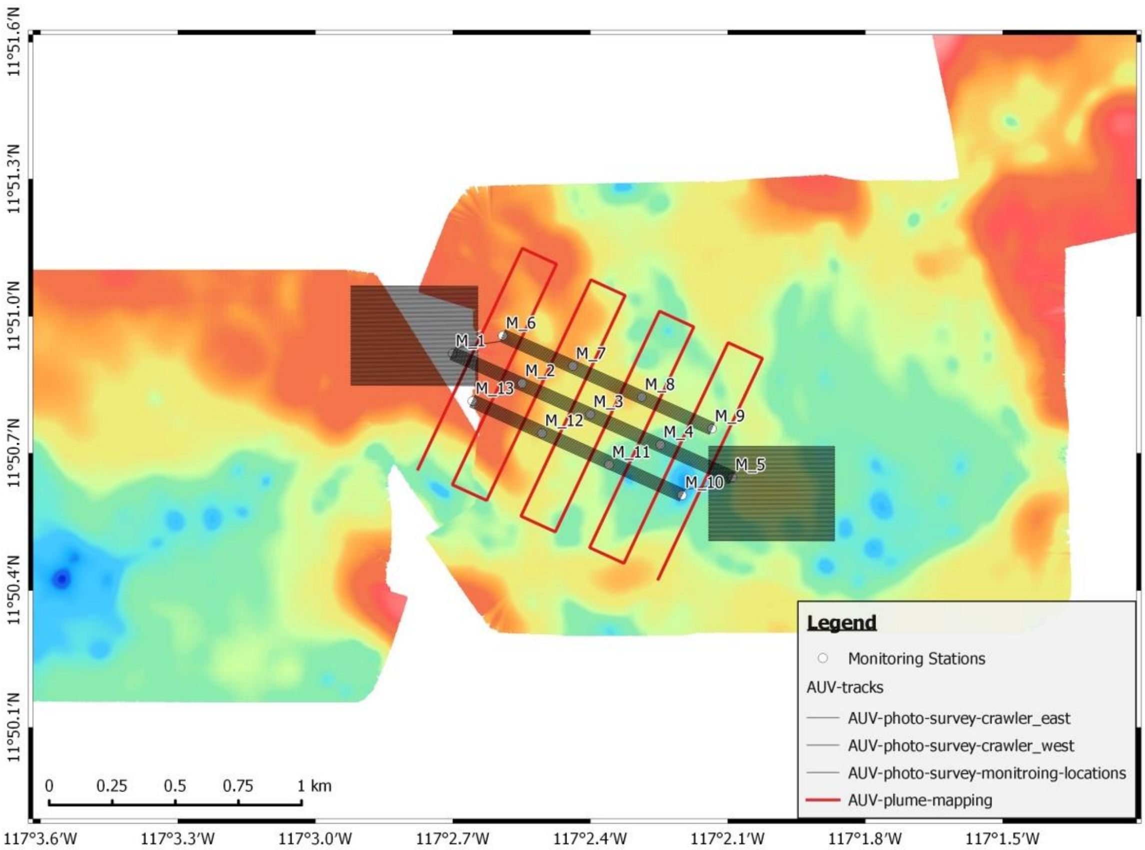


Figure 6.1: Schematic layout of the monitoring array in relation to two potential mining sites. The two alternative mining sites indicate our strategy to adapt to changing bottom current directions during the time of the collector trial: since placing the monitoring array is very time-consuming, we plan to shift the area of the collector trial, if necessary, to ensure effective monitoring of the sediment plume. Hence, both areas will be sampled and surveyed prior to and after the plume experiment as IRZ and PIRZ in the tested EMMP. Wider AUV surveys are planned to cover the entire experiment area of 10x10 km^2.

The second part of the EMMP layout is concerned with the monitoring array and will be based primarily on the model results of Task 6.1. In general the array will be consist of stationary landers (DOS and BoBo of GEOMAR and NIOZ, equipped with CTDs, cameras, ADCPs, sediment traps) and short moorings with ADCP and CTDs (BGR) as well as bottom stations consisting of e.g. upward-looking ADCPs, CTDs with optical sensors, particle cameras and ruler-boards (i.e. chess-boards with an upward-directed stick with centimeter marks, see WP2). Depending on availability, a total of 13 to 16 monitoring stations will be prepared and distributed over a ~1-km^2 large monitoring array (Figure 6.1). This layout is based on observations of particle fallout areas of an Epibenthic Sledge disturbance experiment during SO239 (Martinez & Haeckel, 2015).

Based on the results of Task 6.1, pre-impact studies, and the bottom current conditions at the time of the collector trial, the EMMP layout will be adjusted during the cruise, if necessary.

Task 6.2.3 Cruise station time planning: In cooperation with partners of WP1, 2 and 3 and based on results from Tasks 6.2.1 and 6.2.2, a detailed cruise plan will be developed accounting for AUV survey times, biological, geological and biogeochemical field work as well as deployment times for moorings. Technical pre-conditions of the collector system and safety issues for the two-vessel operation as well as real-time communication will be prepared with DEME. Monitoring technologies as outlined above and described in WP2, as well as a large amount of monitoring equipment and sensors must be precisely deployed and intercalibrated at suitable facilities of partner institutions.

Task 6.3: Onsite pre-impact assessment (outlined in WP1, 2, 3): enabling and overseeing a coordinated approach of the pre-impact assessment within the designated zones. This will include improved habitat characterization using statistical methods to make biological/optical sampling more effective with regards to the habitat distribution and particle characteristics (size/settling).

Task 6.4: Small scale in-situ experiments related to plume behavior (outlined in WP2 and 3): enabling and overseeing a coordinated approach of the in-situ experiments and observations of the plume behavior including the injection of phytodetritus (local species cultivated onboard) into small in-situ plumes to determine changes in aggregation behavior; and plumes of different sediment densities released by the ROV to ground-truth particle camera data.

Task 6.5: In-situ monitoring of the collector plume experiment (outlined in WP1, 2, 3): this task involves all previously mentioned technologies. CCT1 will oversee a coordinated experiment to ground-truth and validate the plume behavior using stationary and mobile observations with ADCPs, OBS, cameras, particle cameras, tracer particle cameras. Important will be the use of a water column imaging multibeam echo sounder and parallel downward looking ADCP on the ROV to actively map the distribution of the plume from 30 to 50 m above the seafloor. Varying the plume dispersal by changing the release conditions (volume flow, diffusor array, turbulence, sediment concentration) from the collector will be an important experiment in which the ROV will do very close observations.

Task 6.6: Ex-situ experiments related to plume behavior (outlined in WP2 and 3) will provide data for modeling using results from local 10 cm surface sediment-layers. Data on particle size distribution before and after subsequent particle aggregation under conditions of low and moderate turbulence will be provided and resulting w_s, d_i, u_{*cri}, u_{*dep} characteristics under commonly found flow conditions (low flow and eddy induced flow) will feed particle transport models of Task 6.7.

Task 6.7: Near real-time modeling to predict fallout areas (outlined in WP2): During the cruise regular updates of the plume dispersion model will allow for an adaptive monitoring effort. At the same time models can be verified by the field data and observations (see WP2).

Task 6.8: On-site post-impact assessment (outlined in WP1, 2, 3, CCT2): After the experiment all monitoring activities of the pre-impact assessment will be repeated to determine the extent of the fallout area and the thickness of sediment blanketing as well as the impact on fauna, microbial activity and biogeochemical conditions/processes. This will include the determination of blanketing effect/layer thickness by AUV based imagery, possible changes in multi-beam backscatter intensity, measurement by ROV, observation of ruler-boards deployed before the experiment. In addition the resuspension- and aggregation behavior of freshly sedimented plume particles including introduced fluorescent particle tracers will be investigated.

Task 6.9: Evaluating the effectiveness of the CCT1 workflow and used monitoring technologies: This task will evaluate if the above described workflow of planning a plume/impact monitoring campaign/field work covered all important aspects and processes. The performance of the deployed sensors and platforms will be analysed with respect to e.g., detection ranges of particle concentrations and determining the footprint and thickness of the deposited sediment blanket. A best practice guidance document on monitoring technology, layout scheme and workflow will be produced.

Work Schedule

	2018		**2019**				**2020**				**2021**				**2022**
	3	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**
6.1 Exchange with DEME on collector trial	X	X													
6.2 Planning of experiment and cruise	X	X	X												
6.3 Onsite pre-impact assessment			X												
6.4 in-situ plume experiments			X	X											
6.5 Monitoring of the collector trial			X	X											
6.6 Ex-situ plume experiments	X	X	X	X	X	X	X	X							
6.7 Modeling to predict fallout areas			X	X											
6.8 On-site post-impact assessment				X											
6.9 Evaluating workflow & monitoring technologies					X	X	X	X	X	X	X	X			

Milestones/Deliverables

M 6.1 Planning of SONNE cruise and EMMP layout (month 4, GEOMAR)

M 6.2 Evaluation of employed EMMP concept and monitoring technology (month 18, JUB)

D 6.1 Report about recommended workflow for planning of monitoring of Mn-nodule mining operations (month 24, GEOMAR)

D 6.2 Guidance document on suitability of different monitoring technologies (month 36, JUB)

CCT 2: Disturbance effects in time and space

Contributors: AWI, UGhent, NIOZ, GEOMAR, MPI, IFREMER, SGN, UAveiro, UAlgarve, IMAR, ULodz, CIIMAR, NIVA, UNIVPM

Goals / Objectives

Given the interactions of multiple stressors and pressures, an integrated assessment of cumulative and interactive impacts is required reflecting different biological, biogeochemical, and physical data and identifying the sensitivity of different ecosystem components. Furthermore, potential mitigation mechanisms will be investigated by initiating restoration experiments. Specific goals to be adressed by CCT2 are:

- Identification of the scale and magnitude of integrated changes in biological communities and ecosystem function in relation to different disturbance effects
- Development of tools for integrated (cumulative) environmental impact assessment
- Test tools and concepts for recovery facilitation

Progress beyond the State-of-the-Art

Polymetallic nodule mining will increase pressure on abyssal ecosystems which may cause the loss of genetic and species diversity, the fragmentation of natural habitats and the degradation of ecosystem functions (Jones et al. 2017, Gollner et al. 2017). Future mining therefore requires a clear and strong policy that will regulate activities and their pressures on the environment in order to reduce their effect and impact. For policy development by the ISA and the implementation of a sound environmental management plan for regions of interest in the Area (CCT3), more insight is needed in the causal activity-pressure-effect relations of the targeted ecosystem and its components (i.e. species populations and communities, habitats and ecosystem functions), and the cumulative pressures mining activities will exert on ecosystems or their components (Tamis et al. 2015). In particular for the remote and pristine abyss in the Central Eastern Pacific, more data are needed to quantify the impact of mining activities by identifying specific pressures and their cumulative effects on the vulnerability and recovery potential of the ecosystem. Figure 7.1 illustrates potential relations between activities and pressures on different ecosystem components.

An environmental management plan for the CCZ requires that pressures caused by mining activities on the marine ecosystem are kept within acceptable minimum levels. To identify these pressure levels a multitude of environmental assessment (EA) approaches are possible, but given the size of the area and the different stakeholders (concession holders) there is a need for a harmonized and integrated EA approach, one that considers cumulative impacts and at the same time is sufficiently evidence-based. Environmental impact assessment (EIA) is a widely used site-specific tool that identifies potential impacts and integrates then into monitoring schemes and the mitigation hierarchy of avoidance, minimization, restoration and offset measures (Bigard et al. 2017). Given the interactions of multiple stressors and pressures, an integrated assessment is required by combining multiple Lines of Evidence (LOE) that reflect different biological, chemical, and physical data (Bebianno et al. 2015, Caeiro et al. 2017, Mestre et al. 2017). The integration of LOE, through Weight of Evidence (WOE) approaches is one of the tools developed for informed decision making (Weed 2005). Overall, a WOE approach is the process of considering strengths and weaknesses of different types of information or evidence in order to make a decision among competing alternatives (Bebianno et al. 2015, Caeiro et al 2017, Mestre et al. 2017). The WOE approach was recently applied in the study by Mestre et al. (2017) and it revealed useful to detect and quantify the environmental hazard posed by a mine tailings deposit, especially in case of sediment plumes. While few studies have documented the individual effects of the different mining pressures on species and ecosystems (Auguste et al. 2016, Mevenkamp et al. 2017) research on cumulative and interactive impacts of multiple stressors from mining in the abyss is completely lacking.

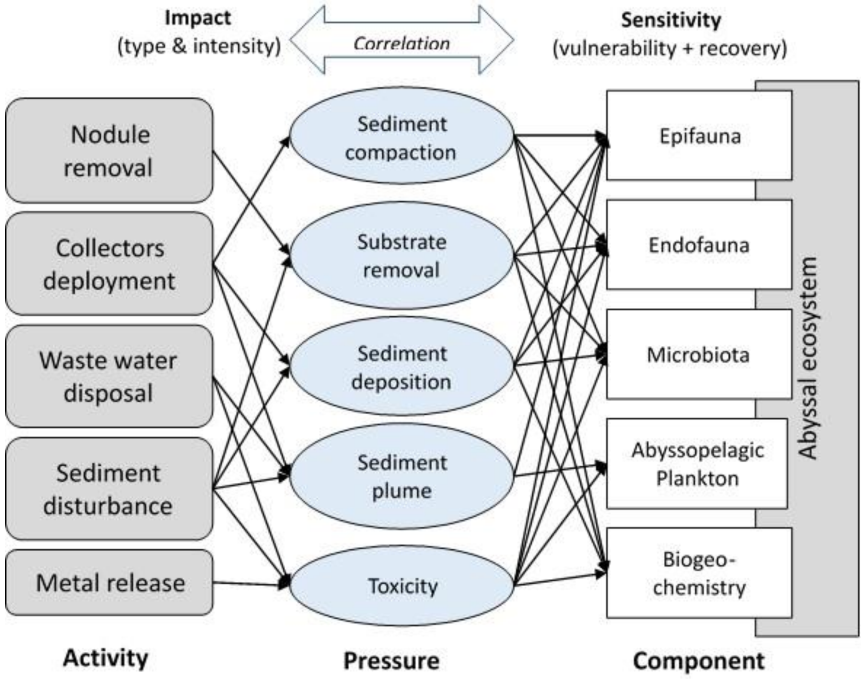


Figure 7.1: Generic outline for cumulative effect assessment of potential nodule mining related activities that may generate pressures on different ecosystem components. The conceptual scheme visualizes potential relationships between impact intensity and sensitivity that needs to be assessed. (modified after Tamis et al. 2017).

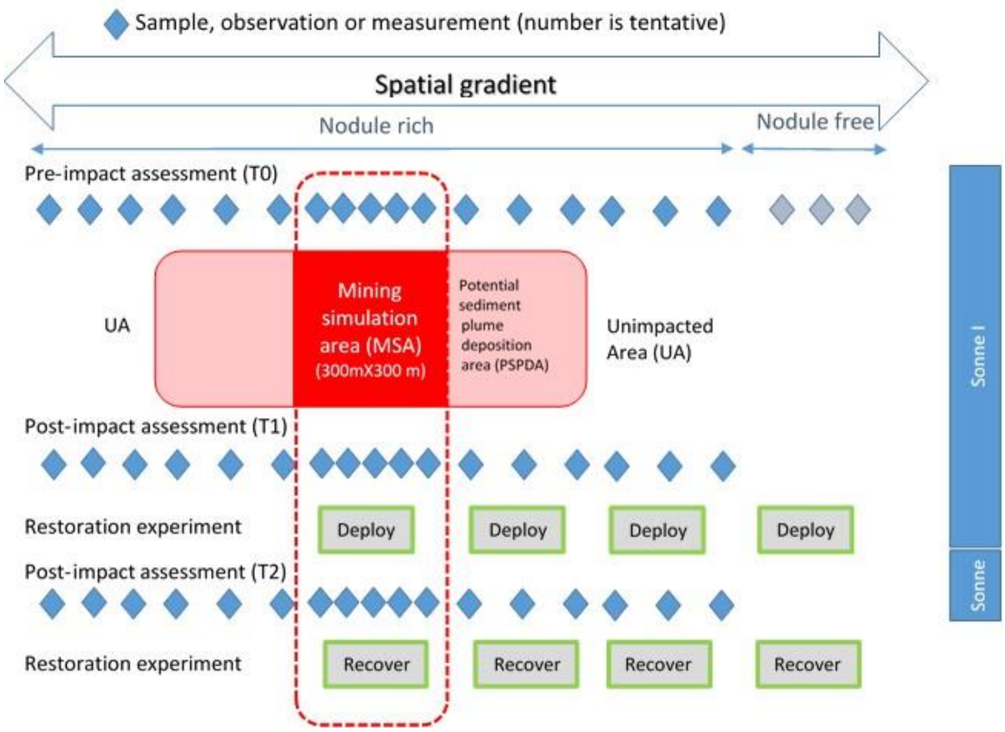


Figure 7.2: Schematic presentation of spatial and temporal coverage of pre- and post impact assessment, and the restoration experiment.

The proposed monitoring of the nodule collector prototype trial in an abyssal nodule field will allow identification of the cumulative impact of different pressures resulting from mining activities on various ecosystem characteristics and identifying the sensitivity of different ecosystem components. A range of variables to identify the intensity of the impact will be assessed pre- and post-disturbance and correlated to different variables for ecosystem structure and function. Figure 7.2 presents the intended activities before and after the collector's deployment. Furthermore, potential mitigation mechanisms will be investigated by initiating restoration experiments (McKenney & Kiesecker 2010). In this project we will test the feasibility of different substrates for recovery of nodule-specific biota.

Work Program

Task 7.1: Linking mining activities to pressures and effects on ecosystem components

Task 7.1.1 Integrate the spatial and temporal variability in (bio)geochemistry, element fluxes, bioturbation, sediment and pore water characteristics, and relate the observed changes after disturbance to specific pressure (and combinations) and their intensity against the observed baseline variability in environmental conditions (AWI, GEOMAR, JUB, MPI, NIOZ, MARUM with input from CCT1 and WP2).

Task 7.1.2 Integrate the spatial and temporal variability in benthic communities (microorganisms, meio-, macro-, and megafauna) with respect to biodiversity, abundances, biomass as identified in WP1 and relate the observed changes after disturbance to specific pressure (and combinations) and their intensity against the observed baseline variability in benthic communities (AWI, MARE, IFREMER, UGhent, ULodz, MPI, NIOZ, CIIMAR, UAveiro, SGN, UNIVPM with input from CCT1, WP2, and WP3)

Task 7.1.3 Integrate the spatial and temporal variability in benthic ecosystem functions (e.g., organic matter processing, microbial growth, food web) as identified in WP 3 and relate the observed changes after disturbance to specific pressure (and combinations) and their intensity against the observed baseline variability in benthic communities (CIIMAR, NIOZ, UGhent, MPI, UNIVPM, GEOMAR)

The integration of results obtained from the different workpackages (WP1, 2 and 3) and CCT1 will be organized in different steps starting from a qualitative and semiquantitative presentation and scoring of pressures and responses of all ecosystem components. This initial step is a first broad scale, low-detailed assessment based on the available information and/or expert judgement and classification schemes (Tamis et al. 2017). The criteria for such assessment is an important part of this process and will be adapted from existing procedures from other marine ecosystems (Halpern et al. 2007, Knights et al. 2015). In a second step a quantitative assessment of intensities of pressures and responses of ecosystem components will be done. This step is required for a focused, high-detailed assessment based on functional relationships. This approach will generate measures of sensitivity based on both empirical data (evidence based) and expert judgement (Stelzenmuller et al. 2015).

Task 7.2: Tools for integrated (cumulative) environmental impact assessment (all partners)

Task 7.2.1 Perform a multiple-scale analysis to test the importance of the observation scale (both spatial and temporal) for impact assessment (SGN, UAveiro, IFREMER, NIOZ, ULodz, UGhent, AWI, GEOMAR, IMAR)

In the framework of an integrated EIA it is important to address the experimental assessment of the scale of analyses (sampling units, surface covered, distance of transect, etc.) and replication necessary to reveal ecologically significant patterns. Perceptions of deep-sea diversity and community composition were observed to change with the scale analysed (Levin et al. 2001). At the temporal scale, ecotoxicological parameters can also identify sublethal effects in deep-sea fauna from hours of exposure to months or years (Company et al. 2006, Auguste et al. 2016, Mestre et al. 2017). Hence, a multiple-scale analysis is proposed in which the importance of the observation scale (both spatial and temporal) is put forward. The possibility of making predictions and extrapolations based on small observation windows for similar ecosystems and distance from impact will be put to the test

Task 7.2.2 Identify the types of impacts (compaction, nodule or surface sediment removal, blanketing, particle concentration and shape in the water column, toxicity, etc) that have the largest effects on benthic communities and functions and determine the relevant ‘intensity thresholds’ (thickness of surface sediment mixed or lost, thickness of blanketing layer, etc) (UGhent, IFREMER + all CCT2 partners)

Task 7.2.3 Identify ‘indicator species’ / ‘indicator groups’ / ‘indicator functions’ as a proxy for effects on specific parts of the benthic ecosystem (e.g., distinct taxonomic or functional groups, size classes, or distinct functions like organic matter remineralization, bioturbation, element and energy transfer in food webs) or the ecosystem in general (sensu ‘seafloor integrity’) (SGN+all CCT2 partners)

Identification of tresholds and indicators is important for effective environmental management and monitoring of deep-water mining projects. Both ensure that consistent and representative environmental measurements are being obtained in monitoring programmes. There is little consensus on the appropriate indicators for deep-sea mining. However, the outcomes of experimental assessment, WP1, WP2, and WP3, which evaluate a wide range of potential indicators, will be used to identify suitable indicators and to assess how they change in response to the impact. A workshop is proposed to evaluate and collate data from these assessments and greatly advance progress in identification of indicators and documentation of their expected responses

Task 7.2.4 Identify robust approaches for ecological impact assessment (e.g. WOE) (UAlgarve + all CCT2 partners)

Here we analyse to what extent general patterns in response to specific impacts can be identified that hold for different benthic biota and functions (i.e., addressing the greater question how much of the mining effects can be generalized / predicted based on impact-monitoring alone). In addition different environmental risk assessment tools (such as WOE) will be tested using the gathered data on the best indicators identified in the previous workshops. The results of this workshop should result in recommendations for the best approach to be applied to deep-sea mining.

Task 7.3: Colonization experiment (NIOZ, UGhent, SGN, MPI, UAveiro, NIVA, GEOMAR)

Task 7.3.1 Test the feasibility of artificial hard substrates for restoration action through time and space and explore the role of substrate type for settlement success of biota, including early formation of microbial biofilms, and impact on sediment biogeochemistry (NIOZ, SGN, AWI, JUB, NOC, UGhent, MPI, UAveiro, NIVA)

Task 7.3.2 Explore the role of ecosystem engineers for biodiversity in manganese nodule fields (NIOZ, SGN, CIIMAR)

Artificial settlement substrates will be deployed after the impact at the site directly disturbed during the collector trial, in the area of indirect effect (sediment plume), as well as no-impact area with and without nodules. Per location and time different substrates will be deployed. In addition INDEEP frames (http://www.indeep-project.org) may be deployed to compare the biota that settles in the CCZ with those from different locations around the world. Recovery is planned after one to two years. To account for the expected slow-growth of sessile fauna, we deploy in addition substrates that may be recovered after more years. To study the function of ecosystem engineers at nodule fields, artificial stalked sponges will be mounted on concrete blocks to simulate natural sponges which are known to host a diverse community of fauna. To our knowledge, our approach is unique in its field and will provide substantial information on the usefulness of substrates as mitigation action as well as on function of hard substrates for biodiversity at nodule fields. Faunal data from settlement substrates are compared to the data from the environmental impact assessment to unravel the role of potential diversity enrichment of substrates after the test-mining event. Genetic connectivity studies (see also WP 1) are used to unravel the role of connectivity on recovery processes.

MPI will sample biofilms from the recovered colonization objects for 16S rRNA gene tag sequencing to assess the microbial communities colonizing the surfaces and how they differ with the nature of the substrate and - given that subsequent sampling can take place later in the project. A video-guided ‘nodule dropper’ will be used to deploy individual colonization structures/artificial nodules remotely-triggered directly at the seafloor for later visual inspection and sampling by ROV.

AWI, JUB and GEOMAR will assess the impact of the different substrates (artificial nodules/concrete, nodule garbage after processing, clean nodules as reference) dropped on the seafloor (see earlier) and their specific microbial and faunal colonizations on the geochemistry of the surrounding and underlying (disturbed) surface sediment. In particular, we will determine whether and how the different substrates influence and control the regeneration of the impacted surface sediments with respect to redox zonation and biogeochemical processes.

Work Schedule

	2018		**2019**				**2020**				**2021**				**2022**
	3	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**
7.1 Linking mining activities to pressures and effects on ecosystem components															
7.1.1 Integrate biota							X	X	X	X	X	X	X		
7.1.2 Integrate biogeochemistry							X	X	X	X	X	X	X		
7.1.3 Integrate functions													X	X	X
7.2 Tools for cumulative EIA															
7.2.1 Multi-scale analysis									X	X	X	X	X	X	X
7.2.2 Intensity thresholds									X	X	X	X	X	X	
7.2.3 Indicators									X	X	X	X	X	X	
7.2.4 EIA approaches														X	X
7.3 Colonization															
7.3.1 Faunal recolonization	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
7.3.2 Ecosystem engineers	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Milestones/Deliverables

M 7.1 Workshop on quantitative assessment of intensities (including scoring criteria) of pressures and responses of all ecosystem components (month 24, UGhent, AWI)

M 7.2 Workshop on scales, indicators and tresholds (month 30, SGN, IFREMER)

M 7.3 Workshop on integrated analysis of ecosystem responses and environmental impact assessment (month 36, UAlgarve)

D 7.1 Report on different ecosystem component responses and sensitivities to specific pressures (interactions and intensities) from mining activities (month 36, SGN)

D 7.2 Report with recommendations on scales, indicators & thresholds for EIA (month 39, UGhent)

D 7.3 Report on recolonization by fauna and microbiota, and adjacent sediment biogeochemistry (month 41, AWI)

CCT 3: Environmental risk assessment & policy recommendations

Contributors: DNVGL, UKiel, ISA, BGR, UAlgarve, GEOMAR, SNF

Goals / Objectives

Explore how the knowledge of the environmental impacts and risks as well as concepts for monitoring and spatial management of deep sea mining operations can be implemented into appropriate legal frameworks of ISA, the EU and individual countries.

Specific topics to be addressed are:

- Identification of pathways towards developing a sound methodology of risk assessment for the use of marine resources that takes into consideration the state of knowledge and evolving research on marine ecosystems.
- Propose methodologies for risk assessment of environmental hazard of plumes, like Weight of Evidence (WOE) and Environmental Hazard and Impact Identification (ENVID).
- Develop concepts for minimizing harmful impacts on the environment arising from mining, such as: spatial management planning of mining operations; defining criteria for preservation reference zones, conservation areas, additional marine protected areas; applying the concept of 'good environmental status' from environmental management
- Establishment of non-compliance procedures and a legal framework for a liability regime for environmental damage
- Information exchange with ISA and their contractors, EU, countries with marine mineral resources, mining-interested industry, NGOs
- Establish a systematic approach for estimating the overall benefits, costs and risks stemming from seabed operations, this implies undertaking cost-benefit and risk-benefit analysis.

Progress beyond the State-of-the-Art

MiningImpact 2 will contribute to the development of methods for environmental risk assessments of marine resources and ecosystems where exploration or exploitation of marine mineral resources is planned to take place. State-of-the-Art is that a substantial amount of research has been done to identify environmental risks but practical methods to evaluate risks and integrate them for practical use in exploration or exploitation has been lacking. A development of such methods like Weight of Evidence (WOE) and Environmental Hazard and Impact Identification (ENVID) will be a significant progress beyond the State-of-the-Art.

There is previous joint experience from the ECO2 project where DNVGL and GEOMAR co-operated in applying ERA to anthropogenic impacts in the marine environment (Wallmann et al. 2015).

The Weight of Evidence (WOE) approach has been successfully applied to classify plume resuspension hazards in the submarine mine tailings deposit of Portmán Bay, Spain, during the EU-FP7 project MIDAS (Mestre et al. 2017). The impact of plumes during the collector test will be assessed in WP2 using the WOE approach. After validation in a deep-sea setting, this methodology can be incorporated in environmental risk assessment guidelines to classify plume hazard, and be integrated in policy recommendations.

The purpose of an environmental aspect and hazard identification (ENVID) is to identify both accidental events and planned operational procedures related to a mining operation (exploration or exploitation) that can cause an impact on the environment. The ENVID method that is described in DNVGL's recommended practice (DNV GL 2016) will be validated during the monitoring of nodule collector test and a guideline for polymetallic nodule mining in the deep sea will be developed based on the assessed direct and indirect environmental impacts, i.e. removal of nodules and associated seafloor habitat in the mined area and blanketing of the surrounding seafloor by re-deposition of the suspended sediment plume. Integration of the scientific results of the first project phase will also allow addressing the longer-term mining impacts.

Key instruments in ISA's draft environmental regulations for minimizing the impacts arising from deep-sea mining are (1) to define suitable indicators for ecosystem health and acceptable threshold values thereof to avoid causing serious harm to abyssal ecosystems as well as (2) to develop strategic and regional environmental management plans (SEMP/REMP) to minimize or prevent the risk of large-scale adverse effects. Currently the only spatial planning that has been realized is the definition of the APEIs (Areas of Particular Environmental Interest) in the CCZ. However, spatial planning is also needed within the license areas. During the first project phase and the EU-FP7 project MIDAS (Jones et al. 2016), first conceptual ideas have been developed that include multiple impact and preservation reference zones to address both, uncertainties in the sediment plume dispersal and natural variability. A first EMMP concept (Fig. 8.1) will be tested in the course of the SONNE cruise in 2019 (see monitoring plan of CCT1). CCT3 will further develop this concept in conjunction with DNVGL's ENVID process.

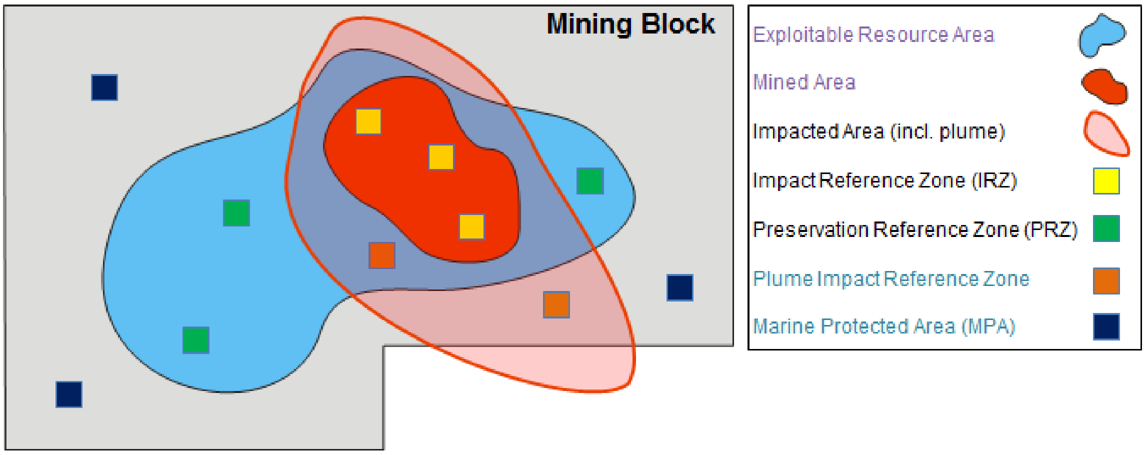


Fig. 8.1: Concept of an environmental management & monitoring plan (EMMP) with multiple impact and preservation reference zones to deal with uncertainties in the sediment plume dispersal and to account for natural spatial variability. (modified from Jones et al. 2016)

Work Program

Task 8.1 Description of the structure of the models

Results from WP2 on the WOE approach will be integrated in the proposed recommendations for the environmental risk assessment (ERA) guidelines.

The environmental aspect and hazard identification (ENVID) method will as a first test be tried out against the example case in DNVGL's recommended practice (DNV GL 2016) which describes mining of polymetallic nodules located in the Clarion-Clipperton Zone at a water depth of 5,000 m. Based on the test the ENVID method will be applied to the nodule collector trial. In the first stage the environmental hazards will be identified and then introduced into the ENVID method by assessing probabilities and consequences of the identified hazards. The hazards that constitute an unacceptable risk will be going to the second stage where risk-reducing actions are introduced. The final and third stage will be the recommendations for the mining operation based on the ENVID and restrictions where the risk is still too high after risk-reducing actions have been taken.

GEOMAR will analyze the EMMP concept tested during the SONNE cruise monitoring the collector trial (see CCT1). In conjunction with DNVGL's ENVID process and the results of

CCT2 improved spatial management concepts will be developed. Appropriate environmental management strategies can contribute to the discussion on how to deal with scientific uncertainties in environmental legislation, such as ISA's exploitation mining code.

In this task the structure of how to use the risk assessment models will be developed. This structure will be showing how the data from the collector trial will be integrated into the models.

Task 8.2 Report on outline of WOE and ENVID model

In order to address the pressures of resource extraction on the environment we will identify possible hazards (e.g. release of large sediment plumes and dispersion of toxic substances), evaluate their environmental impacts, and assess the risk of those events occurring. We will explore how the guidelines for impact assessment recently drafted by the International Seabed Authority could be expanded into a legal framework for environmental risk assessment, taking into account the continuously growing number of deep-sea observations and current practices in offshore hydrocarbon industry. While impact assessment is a standard prerequisite for seafloor activities, environmental risk assessment is a process that has not yet been fully explored and requires a synthesis of scientific data, a foundation in decision-theory and allowances for political and legal considerations. We will assess whether or not regulation at an international level improves the adequacy of national regulation of states with low regulatory capacity. We will use these new insights to support the International Seabed Authority and other regulators to improve soft and hard law codifications that balance economic needs against environmental considerations, based on improved scientific knowledge and newly developed risk assessment processes.

Based on analyses of seabed (and sub-surface) operations, we will establish a coherent method for analysing relevant costs and benefits (benefit-cost analysis). The method will comply with the general guidelines at national level and EU-level.

This involves identifying relevant stakeholders to the operations, both participating agents and non-participating agents. Related to this, it is important to identify a relevant and realistic counterfactual baseline scenario.

Further, we will identify the potential for external effects of the operations. Real negative and positive effects on both participating and non-participating agents will be important for the overall desirability of operations. In these instances, private entities do not fully take into account societal benefits and/or costs. Private entities may in these instances have perverse incentives when undertaking seabed operations. In particular, when effects of the operations are multinational, the proper analyses of the distribution of positive and negative externalities are important.

This task will be based on the identification of the possible hazards and give the outline for the WOE and ENVID model.

Task 8.3 Guidance document for methodologies for risk assessment of environmental hazard

Moreover, the analysis will involve a comprehensive economic analysis of risks involved, specifically, we will analyse risks in relation to expected benefits (similar to risk-benefit ratio). This involves analyses of expected future risk and perceived risk of the operations. While the WoE and ENVID will identify and quantify environmental risks, this part of the project will relate or convert these aspects of seabed operations to the other economic benefits and costs.

An important part of the economic analysis will be identifying how different project designs may affect benefits, costs and risks. While many benefits, costs and risks will be evaluated in monetary terms, it will be important to also include aspects of benefits, costs and risks that cannot be evaluated using monetary values. It is expected that some risks identified using WoE and ENVID optimally should be evaluated using non-monetary terms.

Particular attention need to be put on the potential for irreversible effects, defined as negative effects of operations impossible or extremely costly to reverse. The potential for such effects can be identified using WoE and ENVID.

An important part of the project is the valuation of natural resources that currently has no opportunity cost. The opportunity cost of a resource is defined as the potential gain from the best alternative foregone. However, that a resource has zero opportunity cost does not imply that the resource as no value. This will be important when analysing deep-sea mining operations.

When project-design significantly affects benefits, costs and risks, the optimal regulatory framework should rely on this information. Only in this way will the regulatory framework provide proper incentives for companies to undertake seabed operations in a societal desirable manner.

By providing a coherent analysis of societal benefits, costs and risks of seabed operations, compared to the counterfactual scenario, we will be able to provide recommendations regarding seabed operations for decision-makers. The recommendations will be given in the form of a guidance document which describes methodologies for risk assessment of environmental hazards of deep-sea mining.

Work Schedule

	2018		**2019**				**2020**				**2021**				**2022**
	3	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**
8.1 Description of the structure of the models															
Description of model structures	X	X	X	X											
Develop & analyze EMMP concepts	X	X	X	X	X	X									
Validation of WOE model						X	X	X	X	X					
8.2 Report on outline of WOE and ENVID model															
Explore ERA possibilities in ISA draft regulations				X	X	X	X	X							
Develop method for cost-benefit analysis							X	X	X	X	X	X			
8.3 Guidance document on methodologies for risk assessment of environmental hazard															
Economic risk analysis								X	X	X	X	X	X	X	
Formulate improved regulations											X	X	X	X	X
Prepare & publish guidance document for ERA methodologies															X

Milestones/Deliverables

M 8.1 Description of the structure of the models showing how the data from the collector trial will be integrated into the models (month 12, UAlgarve)

M 8.2 Validation of WOE model achieved, recommendation on this methodology ready to be incorporated into guidance document (month 30, DNV)

D 8.1 Report on outline of WOE and ENVID model (month 24, DNV)

D 8.2 Guidance document on methodologies for risk assessment of environmental hazards of deep-sea mining (month 43, DNV)

Administrative Details

List of Partners			
No	**Partner**	**Acronym**	**Country**
1	GEOMAR Helmholtz Centre for Ocean Research Kiel	GEOMAR	Germany
2	Max Planck Institute for Marine Microbiology	MPI	Germany
3	Senckenberg Gesellschaft für Naturforschung	SGN	Germany
4	Bielefeld University	UBielefeld	Germany
5	Alfred Wegener Institute Helmholtz Centre for Polar & Marine Research	AWI	Germany
6	Jacobs University Bremen gGmbH	JUB	Germany
7	Federal Institute for Geosciences and Natural Resources	BGR	Germany
8	MARUM - Center for Marine Environmental Science, University Bremen	MARUM	Germany
9	Walther Schücking Institute for International Law, Kiel University	UKiel	Germany
10	NIOZ – Royal Netherlands Institute for Sea Research	NIOZ	The Netherlands
11	Utrecht University	UUtrecht	The Netherlands
12	Delft University of Technology	TUDelft	The Netherlands
13	Ghent University	UGent	Belgium
14	Royal Belgian Institute of Natural Sciences	RBINS	Belgium
15	DNVGL	DNVGL	Norway
16	Norwegian Institute for Water Research	NIVA	Norway
17	Uni Research	UResearch	Norway
18	GRID-Arendal	GRIDA	Norway
19	Norwegian University of Science and Technology	NTNU	Norway
20	Universidade de Aveiro (CESAM)	UAveiro	Portugal
21	CIIMAR LA - Interdisciplinary Centre of Marine & Environmental Research	CIIMAR	Portugal
22	CIMA, Universidade do Algarve	UAlgarve	Portugal
23	IPMA - Instituto Português do Mar e da Atmosfera	IPMA	Portugal
24	IMAR (Institute of Marine Research)	IMAR	Portugal
25	Ifremer	Ifremer	France
26	Polytechnic University of Marche	UniVPM	Italy
27	Natural History Museum	NHM	U.K.
28	University of Southampton	USou	U.K.
29	University of Łódź	ULodz	Poland
30	International Seabed Authority	ISA	Jamaica
31	Centre for applied research at NHH	SNF	Norway

Project Summary

MiningImpact 2 will extend its work towards three major research interests concerning deep-sea mining: (a) the larger scale environmental impact caused by the suspended sediment plume, (b) the regional connectivity of species and the biodiversity of biological assemblages and their resilience to impacts, and (c) the integrated effects on ecosystem functions, such as the benthic foodweb and biogeochemical processes.

In this context, key objectives of the project are: (1) to develop and test monitoring concepts and strategies for deep-sea mining operations; (2) to develop standardization procedures for monitoring and definitions for indicators of a good environmental status; (3) to investigate potential mitigation measures, such as spatial management plans of mining operations and means to facilitate ecosystem recovery; (4) to develop sound methodologies to assess the environmental risks and estimate benefits, costs and risks; and (5) to explore how uncertainties in the knowledge of impacts can be implemented into appropriate regulatory frameworks.

While the first project phase could investigate only experimental and/or rather small-scale disturbances of the seafloor, in the second phase a comprehensive monitoring program will be devoted to the industrial test of the prototype nodule collector system of the Belgian contractor DEME-GSR. The equipment trial intends to harvest nodules from the seabed in areas that are approximately 300 x 300 m^2 large, located in the Belgian and the German contract areas of the CCZ. Thus, MiningImpact 2 will collect independent scientific information on the environmental impacts of this operation. Here, the primary focus is on constraining and quantifying the temporal dynamics and characteristics of the suspended sediment plume, the spatial footprint of the deposited sediment blanket, and the induced effects on the abyssal ecosystem.

Keywords: deep-sea mining, polymetallic nodules, environmental impact, ecosystem recovery, monitoring

Project Structure		
	Title	Lead partner
WP 1	Biodiversity, connectivity, resilience	IMAR (Ana Colaco) UAveiro (Marina Cunha)
WP2	Fate and toxicity of the sediment plume	NIOZ (Henko de Stigter) UAlgarve (Nelia Mestre)
WP 3	Biogeochemistry and ecosystem functioning	MPI (Felix Janssen) CIIMAR (Teresa Amaro)
WP 4	Data and sample management	GEOMAR (Matthias Haeckel + Pina Springer)
WP 5	Project dissemination and coordination	GEOMAR (Matthias Haeckel + Kristin Hamann)
CCT1	Plume monitoring and habitat/disturbance characterization	GEOMAR (Jens Greinert) JUB (Laurenz Thomsen)
CCT2	Disturbance effects in time and space	UGhent (Ann Vanreusel) AWI (Sabine Kasten)
CCT3	Environmental risk assessment & policy recommendations	DNVGL (Jens Laugensen) UKiel (Erik van Doorn)

References/Publications

Scientific Publications (top 5 of proponents)

No.	Reference
1	Vanreusel, A., Hilario, A., Ribeiro, P.A., Menot, L., Martinez-Arbizu, P. (2016). Threatened by mining, polymetallic nodules are required to preserve abyssal epifauna. Scientific Reports 6, 26908.
2	Jones, D.O.B., Kaiser, S., Sweetman, A.K., Smith, C.R., Menot, L., Vink, A., Trueblood, D., Greinert, J., Billett, D.S.M., Martinez Arbizu, P., Radziejewska, T., Singh, R., Ingole, B., Stratmann, T., Simon-Lledo, E., Durden, J.M., Clark, M.R. (2017). Biological responses to disturbance from simulated deep-sea polymetallic nodule mining. *PLOSOne*, DOI:10.1371/journal.pone.0171750.
3	Dell'Anno A., Danovaro R. (2005). Extracellular DNA plays a key role in deep-sea ecosystem functioning. Science 309, 2179.
4	Gollner, S., Kaiser, S., Menzel, L., Jones, D.O.B., Brown, A., Mestre, N.C., van Oevelen, D., Menot, L., Colaco, A., Canals, M., Cuvelier, D., Durden, J.M., Gebruk, A., Egho, G.A., Haeckel, M., Marcon, Y., Mevenkamp, L., Morato, T., Pham, C.K., Purser, A., Sanchez-Vidal, A., Vanreusel, A., Vink, A., Martinez Arbizu, P. (2017). Resilience of benthic deep-sea fauna to mining activities. Marine Environmental Research 129, 76-101.
5	Lim, S.C., Wiklund, H., Glover, A.G., Dahlgren, T.G., Tan, K.S. (2017). A new genus and species of abyssal sponge commonly encrusting polymetallic nodules in the Clarion-Clipperton Zone, East Pacific Ocean. Systematics and Biodiversity, 1-13.

Other relevant publications with respect to application

1) Brown, A., Wright, R., Mevenkamp, L,. Hauton, C. (2017). A comparative experimental approach to ecotoxicology in shallow-water and deep-sea holothurians suggests similar behavioural responses. Aquatic Toxicology. doi:10.1016/j.aquatox.2017.06.028.
2) Corinaldesi C., Barucca M., Luna G.M., Dell'Anno A. (2011). Preservation, origin and genetic imprint of extracellular DNA in permanently anoxic deep-sea sediments. Molecular Ecology 20, 642-654.
3) Corinaldesi, C. (2015). New perspectives in benthic deep-sea microbial ecology, Frontiers in Marine Science, doi:10.3389/fmars.2015.00017.
4) Dahlgren, T.G., Wiklund, H., Rabone, M., Amon, D.J., Ikebe, C., Watling, L., Smith, C.R., Glover, A.G. (2016). Abyssal fauna of the UK-1 polymetallic nodule exploration claim, Clarion-Clipperton Zone, central Pacific Ocean: Cnidaria. Biodiversity Data Journal 4, e9277.
5) Danovaro R. (2010). Methods for the Study of Deep-Sea Sediments, Their Functioning and Biodiversity. CRC Press, Taylor & Francis Group.
6) DNV GL. (2016). Recommended Practice. Managing environmental aspects and impacts of seabed mining. DNV GL-RP-O601 Edition September 2016.
7) Glover, A., Dahlgren, T., Taboada, S., Paterson, G., Wiklund, H., Waeschenbach, A., et al. (2016a). The London Workshop on the Biogeography and Connectivity of the Clarion-Clipperton Zone. Research Ideas and Outcomes, 2, e10528–47.
8) Glover, A., Wiklund, H., Rabone, M., Amon, D., Smith, C., O'Hara, T., Mah, C.L., Dahlgren, T.G. (2016b). Abyssal fauna of the UK-1 polymetallic nodule exploration claim, Clarion-Clipperton Zone, central Pacific Ocean: Echinodermata. Biodiversity Data Journal 4: e7251–48.
9) Glover, A., Dahlgren, T.G., Wiklund, H., Mohrbeck, I., & Smith, C.R. (2015). An End-to-End DNA Taxonomy Methodology for Benthic Biodiversity Survey in the Clarion-Clipperton Zone, Central Pacific Abyss. Journal of Marine Science and Engineering 4(1), 2.

10) Gollner, S., Stuckas, H., Kihara, T.C., Laurent, S., Kodami, S., Martinez Arbizu, P. (2016). Mitochondrial DNA analyses indicate high diversity, expansive population growth and high genetic connectivity of vent copepods (Dirivultidae) across different oceans. PLoS ONE 11, e0163776.

11) Haeckel, M., König, I., Trautwein A.X., Suess, E. (2001). Pore water profiles and numerical modelling of biogeochemical processes in Peru Basin deep-sea sediments, Deep-Sea Research II 48: 3713-3736.

12) Hein, J.R., Koschinsky, A., 2014. Deep-ocean ferromanganese crusts and nodules. In: Holland, H., Turekian, K. (eds.) Treatise on Geochemistry, Vol. 13, Elsevier, pp. 273-291.

13) Hilário, A., Metaxas, A., Gaudron, S.M., Howell, K.L., Mercier, A., Mestre, N.C., Ross, R.E., Thurnherr, A.M., Young, C. (2015). Estimating dispersal distance in the deep sea: challenges and applications to marine reserves. Frontiers in Marine Science 2, doi:10.3389/fmars.2015.00006.

14) Janssen, A., Kaiser, S., Meißner, K., Brenke, N., Menot, L., Martínez Arbizu, P., (2015). A reverse taxonomic approach to assess macrofaunal distribution patterns in abyssal Pacific polymetallic nodule fields. PlosOne 10(2), e0117790.

15) König, I., Haeckel, M., Lougear, A., Suess E., Trautwein, A. X. (2001). A geochemical model of the Peru Basin deep-sea floor—and the response of the system to technical impacts. Deep Sea Research Part II: Topical Studies in Oceanography 48(17–18). 3737-3756.

16) Koschinsky, A., Winkler, A., Fritsche, U. (2003). Importance of different types of marine particles for the scavenging of heavy metals in the deep-sea. Applied Geochemistry 18: 693-710.

17) Langenkämper D., Zurowietz M., Schoening T., Nattkemper T.W. (2017). BIIGLE 2.0 - browsing and annotating large marine image collections. Frontiers in Marine Science 4, 83.

18) Mevenkamp, L., Stratmann, T., Guilini, K., Moodley, L., Van Oevelen, D., Vanreusel, A., Westerlund, S., Sweetman, A.K. (2017); Impaired short-term functioning of a benthic community from a deep Norwegian Fjord following deposition of mine tailings and sediments, Frontiers in Marine Science, https://doi.org/10.3389/fmars.2017.00169.

19) Mewes, K., Mogollón, J. M., Picard, A., Rühlemann, C., Kuhn, T., Nöthen, K., Kasten, S. (2014). Impact of depositional and biogeochemical processes on small scale variations in nodule abundance in the Clarion-Clipperton Fracture Zone, Deep-Sea Research I, 91: 125-141.

20) Mogollón, J.M., Mewes, K., Kasten, S. (2016). Quantifying manganese and nitrogen cycle coupling in manganese-rich, organic carbon-starved marine sediments: Examples from the Clarion-Clipperton fracture zone. Geophysical Research Letters 43: 7114-7123.

21) Purser, A., & Thomsen, L. (2012). Monitoring strategies for drill cutting discharge in the vicinity of cold-water coral ecosystems. Marine Pollution Bulletin 64(11), 2309–2316.

22) Purser, A., Marcon, Y., Hoving, H-J, Piatowski, U., Eason, D., Vecchione, M., Boetius, A. (2016). Recent observations of deep sea incirrate octopi from three manganese-rich locations in the Pacific Ocean. Current Biology 26(24), R1268-R1269.

23) Schoening, T., Jones, D.O.B., Greinert, J. (2017). Compact-Morphology-based polymetallic Nodule Delineation. Scientific Reports 7, 13338.

24) van Doorn, E. (2016). Environmental aspects of the Mining Code: Preserving humankind's common heritage while opening Pardo's box? 70 Marine Policy (2016) 192-197.

25) Wallmann, K., Haeckel, M., Linke, P., Haffert, L., Schmidt, M., Bünz, S., James, R., Hauton, C., Tsimplis, M., Widdicombe, S., Blackford, J., Queiros, A. M., Connelly, D., Lichtschlag, A., Dewar, M., Chen, B., Baumberger, T., Beaubien, S., Vercelli, S., Proelss, A., Wildenborg, T., Mikunda, T., Nepveu, M., Maynard, C., Finnerty, S., Flach, T., Ahmed, N., Ulfsnes, A., Brooks, L., Moskeland, T., Purcell, M. (2015). Best Practice Guidance for Environmental Risk Assessment for offshore CO2 geological storage, ECO2 Deliverable D14.1, 53 p.

Affiliation with (inter)national research programmes

- Working group “Geochemistry and Biology” of the MARUM-JUB-AWI Initiative (“Initiative on sustainable / environmental-friendly deep-sea mining”), Germany

- DFG Cluster of Excellence “The Future Ocean” at University of Kiel, Germany
- DFG Cluster of Excellence “The Ocean in the Earth System” at Bremen University, Germany
- Blue Nodules (H2020, EU)
- SEDIMENTATION: Resilience of deep-sea benthic fauna to sedimentation from seabed mining. 5-year research programme for the analysis of a deep-sea disturbance experiment on the Chatham Rise (phosphates), main applicant NIWA (Malcolm Clark), financed by MBIE (New Zealand), (study period 2016-2021).
- TREASURE: (Towards Responsible Extraction of Submarine Resources), collaborative academic research project funded by the Technology Foundation of the Netherlands Organisation for Scientific Research (STW-NWO) and industry partners, 2014-2019, coordinator NIOZ, The Netherlands
- MARMINE: Exploitation technologies for marine minerals on the extended Norwegian continental shelf. Norwegian Research Council and Industry (BIA). (2015-2020)
- ECOMINA: Ecosystem-based management for areas targeted by deep-sea mining in the Arctic: a pilot study. MIKON-Framsenteret, Norway (2015).
- PLUMEX: Monitoring of a sediment plume released in mid water, offshore California. Lead by Massachusetts Institute of Technology (Thomas Peacock).

Description of project management

MiningImpact II consists of a multi-national, interdisciplinary consortium of 30 partners from 9 European countries, and 1 international organization (The International Seabed Authority). The scientific work is structured in five work packages thematically linked by three cross-cutting themes (see project structure and proposal text). In order to integrate the scientific work in good project governance, the project is based on a management structure that represents all decision parties in the project (executive board, general assembly, steering committee and a scientific advisory board) and allows an efficient information flow. The management structure is organized by WP 5 and is realized in internal communication strategies and the annual meetings.

Executive Board (Coordinator): The project coordinator is the project’s control body. He reports the projects’s progress (received by SC) to the JPI Oceans secretariat and its management board.

Steering Committee: The SC consists of the WP- and CCT-leaders. The SC is responsible for succesfull work of their respective WP/CCT. Moreover, close collaboration of the SC with the Coordinator ensures close monitoring of the project’s progress (e.g. milestones and deliverables).

General Assembly: The General Assembly consists of all project partners and convenes during the annual meetings. EC, SC and GA discuss the projects’s scientific progress, decide on important dissemination activites and consider the SAB’s policy advices.

Transparency in the project’s communication and decision making is realized in the reciprocal reporting between EC and SC as well as between EC, SC and GA. Moreover, important outcomes will be summarized in the project’s newsletter on the project website.

The project execution is confirmed in regular reports to the national funding agencies (by each national partner group) and an annual progress report to JPI Oceans.

Further project management tasks and goals are defined in WP 5.

Reference list (publications of project partners are underlined)

Alevizos, E., Schoening, T., Koeser, K., Snellen, M., Greinert, J. (submitted) Quantification of the fine-scale distribution of Mn-nodules: insights from AUV multi-beam and imagery data fusion. Biogeosciences.

Aleynik, D., Inall, A., Dale, A., Vink, A. (submitted). Abyssal currents intensified by mesoscale eddies in a proposed mining area in the Tropical Pacific. Nature Geosciences.

Auguste, M., Mestre, N.C., Rocha, T.L., Cardoso, C., Cambon-Bonavita, M.A., Cueff-Gauchard, V., Le Bloa, S., Ravaux, J., Shillito. B,, Zbinden. M., Bebianno, MJ. (2016). Development of an ecotoxicological protocol for the deep-sea fauna using the hydrothermal vent shrimp *Rimicaris exoculata*. Aq Tox. 175:277-285.

Barnett, B. and T. Suzuki (1997). The use of kringing to estimate resedimentation in the JET experiment. Proceedings, international symposium on environmental studies for deep-sea mining.

Bebianno, M.J., Pereira, C.G., Rey, F., Cravo, A., Duarte, D., D'Errico, G., Regoli, F. (2015). Integrated approach to assess ecosystem health in harbor areas. Sci Total Env 514, 92-107.

Bigard, C., Pioch, S. and Thompson, J. D. (2017). The inclusion of biodiversity in environmental impact assessment: Policy-related progress limited by gaps and semantic confusion. Journal of environmental management, 200: 35-45.

Bik, H.M., Porazinska, D.L., Creer, S., Caporaso, J.G., Knight, R., Thomas, WK. (2012a). Sequencing our way towards understanding global eukaryotic biodiversity. Trends in Ecology & Evolution, 27, 233–243.

Billings, A., Kaiser, C., Young, C.M., et al (2017). SyPRID sampler: A large-volume, high-resolution, autonomous, deep-ocean precision plankton sampling system. Deep-Sea Res II 137, 297–306.

Blackall, L.L., Wilson, B., van Oppen, M.J.H. (2015). Coral - the world's most diverse symbiotic ecosystem. Molecular Ecology 24, 5330–5347.

Bluhm, H. (2001). Re-establishment of an abyssal megabenthic community after experimental physical disturbance of the seafloor. Deep-Sea Research II 48, 3841–3868.

Boetius A. (ed.), 2015. RV SONNE Cruise Report SO242-2: JPI OCEANS Ecological Aspects of Deep-Sea Mining, DISCOL Revisited. GEOMAR Report 27, 552 pp.

Boetius, A., Wenzhöfer, F. (2009). In Situ Technologies for Studying Deep-Sea Hotspot Ecosystems, Oceanography 22: 177.

Boschen, R.E., Rowden, A.A., Clark, M.R., Gardner, J.P.A. (2013). Mining of deep-sea seafloor massive sulfides: A review of the deposits, their benthic communities, impacts from mining, regulatory frameworks and management strategies. Ocean & Coastal Management 84, 54-67.

Breuer, E., Stevenson, A.G., Howe, J.A., Carroll, J., Shimmield, G.B. (2004). Drill cutting accumulations in the northern and central North Sea: a review of environ- mental interactions and chemical fate. Mar. Pollut. Bull. 48, 12–25.

Brockett, T., Richards, C. Z. (1994). Deepsea mining simulator for environmental impact studies. Sea Technology 35(8). 77-82.

Brooke, S. D., Holmes, M. W., Young, C. M. (2009). Sediment tolerance of two different morphotypes of the deep-sea coral Lophelia pertusa from the Gulf of Mexico. Marine Ecology Progress Series 390, 137–144.

Brown, A., Wright, R., Mevenkamp, L,. Hauton, C. (2017). A comparative experimental approach to ecotoxicology in shallow-water and deep-sea holothurians suggests similar behavioural responses. Aquatic Toxicology. doi:10.1016/j.aquatox.2017.06.028.

Burford Reiskind, M. O., Coyle, K., Daniels, H. V., Labadie, P., Reiskind, M. H., Roberts, N. B., Roberts, R. B., Schaff, J. and Vargo, E. L. (2016). Development of a universal double-digest RAD sequencing approach for a group of nonmodel, ecologically and economically important insect and fish taxa. Mol Ecol Resour 16, 1303–1314.

Caeiro, S., Vaz-Fernandes, P., Martinho, A.P., Costa, P.M., Silva M.J., Lavinha J., et al. (2017). Environmental risk assessment in a contaminated estuary: an integrated weight of evidence approach as a decision support tool. Ocean & Coast. Manag., 143, 51-62.

Company, R., Serafim, A., Cosson, R., Camus, L., Shillito, B., Fiala-Medioni, A., Bebianno. M.J. (2006). The effect of cadmium on antioxidant responses and the susceptibility to oxidative stress in the hydrothermal vent mussel Bathymodiolus azoricus. Marine Biology 148, 817-25.

Corinaldesi C., Barucca M., Luna G.M., Dell'Anno A. (2011). Preservation, origin and genetic imprint of extracellular DNA in permanently anoxic deep-sea sediments. Molecular Ecology 20, 642-654.

Corinaldesi C., Beolchini F., Dell'Anno A. (2008). Damage and degradation rates of extracellular DNA in marine sediments: implications for the preservation of gene sequences. Molecular Ecology 17, 3939-3951.

Corinaldesi C., Danovaro R., Dell'Anno A. (2005). Simultaneous recovery of extracellular and intracellular DNA suitable for molecular studies from marine sediments. Applied and Environmental Microbiology 71, 46-50

Corinaldesi, C. (2015). New perspectives in benthic deep-sea microbial ecology, Frontiers in Marine Science, doi:10.3389/fmars.2015.00017.

Dahlgren, T.G., Wiklund, H., Rabone, M., Amon, D.J., Ikebe, C., Watling, L., Smith, C.R., Glover, A.G. (2016). Abyssal fauna of the UK-1 polymetallic nodule exploration claim, Clarion-Clipperton Zone, central Pacific Ocean: Cnidaria. Biodiversity Data Journal 4, e9277.

Danovaro R. (2010). Methods for the Study of Deep-Sea Sediments, Their Functioning and Biodiversity. CRC Press, Taylor & Francis Group.

Dell'Anno A., Danovaro R. (2005). Extracellular DNA plays a key role in deep-sea ecosystem functioning. Science 309, 2179.

DeLong, E. F. (2005). Microbial community genomics in the ocean, Nature Reviews Microbiology 3(6). 459-469.

Deusner C., Kossel E., Bigalke N., Haeckel M., Gupta S., Freise M., Anbergen H., Wille T. (2016). The role of high-pressure flow-through experiments for evaluating the mechanical behaviour of gas hydrate-bearing soils. In: Wuttke, Bauer, Sanchez (eds.) Energy Geotechnics. CRCPress, 437-443.

DNV GL. (2016). Recommended Practice. Managing environmental aspects and impacts of seabed mining. DNV GL-RP-O601 Edition September 2016.

Doi, H., Takahara, T., Minamoto, T., Matsuhashi, S., Uchii, K., & Yamanaka, H. (2015). Droplet digital polymerase chain reaction (PCR) outperforms real-time PCR in the detection of environmental DNA from an invasive fish species. Environmental Science & Technology 49(9), 5601–5608.

Dreutter, S (2017). Multisensor microbathymetric habitat mapping with a deep-towed ocean floor observation and bathymetry system (OFOBS). Masters thesis. HafenCity University Hamburg.

Erftemeijer, P.L.A., Riegl, B., Hoeksema, B.W., Todd, P.A. (2012). Environmental impacts of dredging and other sediment disturbances on corals: A review. Marine Pollution Bulletin 64(9), 1737–1765.

European Commission (2008). Directive 2008/56/EC of the EU Parliament and Council on establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32008L0056

Glover, A., Dahlgren, T.G., Wiklund, H., Mohrbeck, I., & Smith, C.R. (2015). An End-to-End DNA Taxonomy Methodology for Benthic Biodiversity Survey in the Clarion-Clipperton Zone, Central Pacific Abyss. Journal of Marine Science and Engineering 4(1), 2.

Glover, A., Dahlgren, T., Taboada, S., Paterson, G., Wiklund, H., Waeschenbach, A., et al. (2016a). The London Workshop on the Biogeography and Connectivity of the Clarion-Clipperton Zone. Research Ideas and Outcomes, 2, e10528–47.

Glover, A., Wiklund, H., Rabone, M., Amon, D., Smith, C., O'Hara, T., Mah, C.L., Dahlgren, T.G. (2016b). Abyssal fauna of the UK-1 polymetallic nodule exploration claim, Clarion-Clipperton Zone, central Pacific Ocean: Echinodermata. Biodiversity Data Journal 4: e7251–48.

Godø, O.R., Klungsøyr, J., Meier, S., Tenningen, E., Purser, A., Thomsen L (2014). Real time observation system for monitoring environmental impact on marine ecosystems from oil drilling operations. Marine pollution bulletin 84.1 (2014). 236-250.

Gollner, S., Govenar, B., Martinez Arbizu, P., Mills, S., Le Bris, N., Weinbauer, M., Shank, T.M., Bright, M. (2015). Differences in recovery between deep-sea hydrothermal vent and vent-proximate communities after a volcanic eruption. Deep-Sea Research I 106, 167-182.

Gollner, S., Kaiser, S., Menzel, L., Jones, D.O.B., Brown, A., Mestre, N.C., van Oevelen, D., Menot, L., Colaco, A., Canals, M., Cuvelier, D., Durden, J.M., Gebruk, A., Egho, G.A., Haeckel, M., Marcon, Y., Mevenkamp, L., Morato, T., Pham, C.K., Purser, A., Sanchez-Vidal, A., Vanreusel, A., Vink, A., Martinez Arbizu, P. (2017). Resilience of benthic deep-sea fauna to mining activities. Marine Environmental Research 129, 76-101.

Gollner, S., Stuckas, H., Kihara, T.C., Laurent, S., Kodami, S., Martinez Arbizu, P. (2016). Mitochondrial DNA analyses indicate high diversity, expansive population growth and high genetic connectivity of vent copepods (Dirivultidae) across different oceans. PLoS ONE 11, e0163776.

Gould, J.W., Hendry, R., Huppert, H.E. (1981). An abyssal topographic experiment. Deep Sea Research Part A. Oceanographic Research Papers 28 (5), 409-440.

Greinert J. (ed.), 2015. RV SONNE Cruise Report SO242-1: JPI OCEANS Ecological Aspects of Deep-Sea Mining, DISCOL Revisited. GEOMAR Report 26, 290 pp.

Haeckel, M., König, I., Trautwein A.X., Suess, E. (2001). Pore water profiles and numerical modelling of biogeochemical processes in Peru Basin deep-sea sediments, Deep-Sea Research II 48: 3713-3736.

Haeckel, M., van Beusekom, J., Wiesner, M., König, I. (2001). The impact of the 1991 Mount Pinatubo tephra fallout on the geochemical environment of the deep-sea sediments in the South China Sea. Earth and Planetary Science Letters 193, 153-168.

Haeckel, M.,König I., Riech V., Weber M. E., Suess E. (2001). Pore water profiles and numerical modelling of biogeochemical processes in Peru Basin deep-sea sediments. Deep-Sea Research II 48(17–18), 3713-3736.

Hall-Spencer, J. M., Pike, J., & Munn, C. B. (2007). Diseases affect cold-water corals too: Eunicella verrucosa (Cnidaria: Gorgonacea) necrosis in SW England. Diseases of aquatic organisms, 76(2), 87-97.

Halpern, B.S., Selkoe, K.A., Micheli, F., Kappel, C.V. (2007). Evaluating and ranking the vulnerability of global marine ecosystems to anthropogenic threats. Conserv Biol 21:1301–1315.

Hannington, M., Jamieson, J., Monecke, T., Petersen, S., Beaulieu, S., 2011. The abundance of seafloor massive sulfide deposits. Geology 39, 1155-1158.

Hein, J.R., Koschinsky, A., 2014. Deep-ocean ferromanganese crusts and nodules. In: Holland, H., Turekian, K. (eds.) Treatise on Geochemistry, Vol. 13, Elsevier, pp. 273-291.

Henkel, S., Kasten, S., Poulton, S.W. and Staubwasser, M. (2016). Determination of the stable iron isotope composition of sequentially leached iron phases in marine sediments. Chemical Geology, 421, 93-102.

Hess, S., Kuhnt, W., 1996. Deep-sea benthic foraminiferal recolonization of the 1991 Mt. Pinatubo ash layer in the South China Sea. Marine Micropaleontology 28, 171-197.

Hilário, A., Metaxas, A., Gaudron, S.M., Howell, K.L., Mercier, A., Mestre, N.C., Ross, R.E., Thurnherr, A.M., Young, C. (2015). Estimating dispersal distance in the deep sea: challenges and applications to marine reserves. Frontiers in Marine Science 2, doi:10.3389/fmars.2015.00006.

Iversen, P.E., Vi Green A.M., Juel Lind, M., Petersen M.R.H., Bakke, T., Lichtenthaler R., Klungsoyr, J., Grafert, T., Natvig, H., Ersvik, M. (2011). The petroleum sector on the Norwegian Continental Shelf – Guidelines for offshore environmental monitoring. Klima-og-forurensingsdirektoratet (Ed.), TA 2949, Klif, Oslo, pp. 1–50.

Jamieson, A. J., Malkocs, T., Piertney, S. B., Fujii, T. & Zhang., Z. (2017). Bioaccumulation of persistent organic pollutants in the deepest ocean fauna. Nature Ecology and Evolution, 1, 1-4.

Jankowski, J.A., Zielke, W. (2001). The mesoscale sediment transport due to technical activities in the deep sea. Deep-Sea Research II 48, 3487-3521.

Janssen, A., Kaiser, S., Meißner, K., Brenke, N., Menot, L., Martínez Arbizu, P., 2015. A reverse taxonomic approach to assess macrofaunal distribution patterns in abyssal Pacific polymetallic nodule fields. PlosOne 10(2), e0117790.

Janssen, F., Vonnahme, T., Molari, M., Wenzhöfer, F., Haeckel, M., Boetius, A. (2017). Effects of experimental polymetallic nodule mining on deep-sea microbial communities and functions (DISCOL experimental area, tropical SE Pacific), Goldschmidt Conference, Paris, 14-18.8.2017.

Järnegren, J., Brooke, S., & Jensen, H. (2017). Effects of drill cuttings on larvae of the cold-water coral Lophelia pertusa. Deep-Sea Research II 137, 454–462.

Jones, D., Durden, J., Murphy, K., Ardron, J., Billett, D., Gjerde, K., Ortega, A., Colaço, A. (2016). Protocols, tools and standards for environmental management of exploitation of deep-sea mineral resources, MIDAS Deliverable 8.5, 150p.

Jones, D.O.B., Kaiser, S., Sweetman, A.K., Smith, C.R., Menot, L., Vink, A., Trueblood, D., Greinert, J., Billett, D.S.M., Arbizu, P.M., Radziejewska, T., Singh, R., Ingole, B., Stratmann, T., Simon-Lledó, E., Durden, J.M., Clark, M.R. (2017). Biological responses to disturbance from simulated deep-sea polymetallic nodule mining. PloS One 12 (2), e0171750, 10.1371/journal.pone.0171750.

Knights, A.M., Piet, G.J., Jongbloed, R.H., Tamis, J.E., White, L., Akoglu, E., Boicenco, L., Churilova, T., Kryvenko, O., Fleming-Lehtinen, V. et al. (2015). An exposure-effect approach for evaluating ecosystem-wide risks from human activities. ICES J Mar Sci Available from: DOI: 10.1093/icesjms/fsu245.

König, I., Haeckel, M., Lougear, A., Suess E., Trautwein, A. X. (2001). A geochemical model of the Peru Basin deep-sea floor—and the response of the system to technical impacts. Deep Sea Research Part II: Topical Studies in Oceanography 48(17–18). 3737-3756.

Koschinsky, A., Winkler, A., Fritsche, U. (2003). Importance of different types of marine particles for the scavenging of heavy metals in the deep-sea. Applied Geochemistry 18: 693-710.

Köster, M. (in prep., 2017). Reactivity and spatial variations of manganese and iron mineral phases in sediments of the Clarion-Clipperton Zone, Pacific Ocean. Master Thesis, University of Bremen.

Kotlinski, R., Stoyanova, V. (1998). Physical, Chemical, And Geological Changes of Marine Environment Caused By the Benthic Impact Experiment At the 10M BIE Site. The 8th International Offshore and Polar Engineering Conference, International Society of Offshore and Polar Engineers.

Laakmann, S., Gerdts, G., Erler, R., Knebelsberger, T., Martínez-Arbizu, P., Raupach, M.J. (2013) Comparison of molecular species identification for North Sea calanoid copepods (Crustacea) using proteome fingerprints and DNA sequences. Molecular Ecology Resources 13, 862-876.

Langenkämper D., Zurowietz M., Schoening T., Nattkemper T.W. (2017). BIIGLE 2.0 - browsing and annotating large marine image collections. Frontiers in Marine Science 4, 83.

Lawler, S. N., Kellogg, C. A., France, S. C., Clostio, R. W., Brooke, S. D., & Ross, S. W. (2016). Coral-Associated Bacterial Diversity Is Conserved across Two Deep-Sea Anthothela Species. Frontiers in Microbiology, 7(14). doi:10.3389/fmicb.2016.00458.

Lekang, K., Thompson, E. M., & Troedsson, C. (2015). A comparison of DNA extraction methods for biodiversity studies of eukaryotes in marine sediments. Aquatic Microbial Ecology 75(1), 15–25.

Lim, S.C., Wiklund, H., Glover, A.G., Dahlgren, T.G., Tan, K.S. (2017). A new genus and species of abyssal sponge commonly encrusting polymetallic nodules in the Clarion-Clipperton Zone, East Pacific Ocean. Systematics and Biodiversity, 1-13.

Marcon, Y., Purser, A. (2017). PAPARA(ZZ)I: An open-source software interface for annotating photographs of the deep sea. SoftwareX 6, 69-80.

Martinez Arbizu P., Haeckel M. (eds.), 2015. RV SONNE Cruise Report SO239: EcoResponse Assessing the Ecology, Connectivity and Resilience of Polymetallic Nodule Field Systems. GEOMAR Report 25, 204 pp.

McKenney, BA., Kiesecker, JM. (2010). Policy Development for Biodiversity Offsets: A Review of Offset Frameworks. ENVIRONMENTAL MANAGEMENT 45:165-176.

Mestre, N.C., Rocha, T.L., Canals, M., Cardoso, C., Danovaro, R., Dell'Anno, A., Gambi, C., Regoli, F., Sànchez-Vidal, A., Bebianno, M.J. (2017). Environmental hazard assessment of a marine mine tailings deposit site and potential implications for deep-sea mining. Environ Poll 228:169-178.

Mevenkamp, L., Stratmann, T., Guilini, K., Moodley, L., Van Oevelen, D., Vanreusel, A., Westerlund, S., Sweetman, A.K. (2017); Impaired short-term functioning of a benthic community from a deep Norwegian Fjord following deposition of mine tailings and sediments, Frontiers in Marine Science, https://doi.org/10.3389/fmars.2017.00169.

Mewes, K., Mogollón, J. M., Picard, A., Rühlemann, C., Kuhn, T., Nöthen, K., Kasten, S. (2014). Impact of depositional and biogeochemical processes on small scale variations in nodule abundance in the Clarion-Clipperton Fracture Zone, Deep-Sea Research I, 91: 125-141.

Middelburg, J. J., Barranguet, C., Boschker, H. T. S., Herman, P. M. J., Moens, T., Heip, C. H. R. (2000). The fate of intertidal microphytobenthos carbon: An in situ 13C-labeling study, Limnology and Oceanography 45(6). 1224-1234.

Miljutin, D.M., Miljutina, M.A., Martinez-Arbizu, P., Galéron, J. (2011). Deep-sea nematode assemblage has not recovered 26 years after experimental mining of polymetallic nodules (Clarion-Clipperton Fracture Zone, Tropical Eastern Pacific). Deep Sea Research Part I: Oceanographic Research Papers 58 (8), 885-897.

Miljutina, M., Miljutin, D., Mahatma, R., Galéron, J. (2010) Deep-sea nematode assemblages of the Clarion-Clipperton Nodule Province (Tropical North-Eastern Pacific). Marine Biodiversity 40, 1-15.

Mogollon J.M., Mewes K., Kasten S., 2016. Quantifying manganese and nitrogen cycle coupling in manganese-rich, organic carbon-starved marine sediments: Examples from the Clarion-Clipperton fracture zone. Geophysical Research Letters 43, 7114-7123.

Morris, K.J., Bett, B.J., Durden, J.M., Benoist, N.M.A., Huvenne, V.A.I., Jones, D.O.B., Robert, K., Ichino, M.C., Wolff, G.A., Ruhl, H.A. (2016). Landscape-scale spatial heterogeneity in phytodetrital cover and megafauna biomass in the abyss links to modest topographic variation. Scientific Reports 6, 34080.

Nakata, K., Kubota, M., Aoki, S., Taguchi, K., 1997. Dispersion of resuspended sediment by ocean mining activity – modelling study. Proceedings of the first International Symposium on Environmental Studies for Deep-Sea Mining, Tokyo, Japan, 169-186.

Neff, J.M. (2008). Estimation of bioavailability of metals from drilling mud barite. Integr. Environ. Assess. Manage. 4 (2), 184–193.

Pabortsava, K., Purser, A., Wagner, H., Thomsen, L. (2011). The influence of drill cuttings on the physical characteristics of phytodetritus. Marine Pollution Bulletin 62, 2170-2180.

Paul, S. A. L., Gaye, B., Haeckel, M., Kasten, S., Koschinsky, A. (submitted). Biogeochemical regeneration of a nodule mining disturbance site: trace metals, DOC and amino acids in deep-sea sediments and pore waters, Frontiers in Marine Science.

Peukert, A., Schoening, T., Alevizos, E., Köser, K., Kwasnitschka, T., Greinert, J. (submitted). Understanding Mn-nodule distribution and related deep-sea mining impacts using AUV-based hydroacoustic sensing and visual observations. Biogeosciences.

Piva F, Ciaprini F, Onorati F, Benedetti M, Fattorini D, Ausili A, Regoli F. (2011). Assessing sediment hazard through a Weight of Evidence approach with bioindicator organisms: a practical model to elaborate data from sediment chemistry, bioavailability, biomarkers and ecotoxicological bioassays. Chemosphere 83:475-485.

Purser, A., & Thomsen, L. (2012). Monitoring strategies for drill cutting discharge in the vicinity of cold-water coral ecosystems. Marine Pollution Bulletin 64(11), 2309–2316.

Purser, A., Marcon, Y., Dreutter, S., Hoge, U., Sablotny, B., Hehemann, L., Lemburg, J., Dorschel, B., Biebow, H., Boetius, A (in press). OFOBS - Ocean Floor Observation and Bathymetry System: A new towed camera / sonar system for deep-sea habitat surveys. IEEE Journal of Oceanic Engineering.

Purser, A., Marcon, Y., Hoving, H-J, Piatowski, U., Eason, D., Vecchione, M., Boetius, A. (2016). Recent observations of deep sea incirrate octopi from three manganese-rich locations in the Pacific Ocean. Current Biology 26(24), R1268-R1269.

Radziejewska, T., 2002. Responses of deep-sea meiobenthic communities to sediment disturbance simulating effects of polymetallic nodule mining. International Reviews Hydrobiology 87, 457-477.

Radziejewska, T., Drzycimski, I., Galtsova, V.V., Kulangieva, L.V., Stoyanova, V., 2001a. Changes in genus-level diversity of meiobenthic free-living nematodes (Nematoda) and harpacticoids (Copepoda Harpacticoida) at an abyssal site following experimental sediment disturbance. Proceedings of the Fourth Ocean Mining Symposium, Szczecin, Poland, 38-43.

Radziejewska, T., Rokicka-Praxmajer, J., Stoyanova, V., 2001b. IOM BIE revisited: meiobenthos at the IOM BIE site 5 years after the experimental disturbance. Proceedings of the Fourth Ocean Mining Symposium, Szczecin, Poland, 63-68.

Rolinski, S., Segschneider, J., Sündermann, J. (2001). Long-term propagation of tailings from deep-sea mining under variable conditions by means of numerical simulations. Deep-Sea Research II 48, 3469–3485.

Ruff, S. E., Biddle, J. F., Teske, A. P., Knittel, K., Boetius, A., Ramette, A. (2015). Global dispersion and local diversification of the methane seep microbiome. Proceedings of the National Academy of Sciences 112(13), 4015-4020.

Rye, H., Reed, M., Frost, T.K., Smit, M.G.D., Durgut, I., Johansen, Ø., Ditlevsen, M.K. (2007). Development of a numerical model for calculating exposure to toxic and non-toxic stressors in the water column and sediment from drilling discharge. Integr. Environ. Assess. Manage. 4 (2), 194–203.

Schoening, T., Jones, D.O.B., Greinert, J. (2017). Compact-Morphology-based polymetallic Nodule Delineation. Scientific Reports 7, 13338.

Simpson, S.L., Campana, O., Ho, K.T. (2016). Sediment toxicity testing. In: Blasco J, Campana O, Chapman P, Hampel M (Eds.), Marine Ecotoxicology: Current Knowledge and Future Issues, 197-235.

Sinniger, F., Pawlowski, J., Harii, S., Gooday, A., Yamamoto, H., Chevaldonne, P., et al. (2016). World-wide analysis of sedimentary DNA reveals major gaps in taxonomic knowledge of deep-sea benthos. Frontiers in Marine Science, 1–29.

Sogin, M. L., Morrison, H. G., Huber, J. A., Welch, D. M., Huse, S. M., Neal, P. R., Arrieta, J. M., Herndl, G. J. (2006). Microbial diversity in deep sea and the underexplored "rare biosphere", PNAS 103, 12115–12120.

Stelzenmüller, V., Fock, H.O., Gimpel, A., Rambo, H., Diekmann, R., Probst, W.N., Callies, U., Bockelmann, F., Neumann, H., Kroncke, I. (2015). Quantitative environmental risk assessments in the context of marine spatial management: Current approaches and some perspectives. ICES J Mar Sci 72:1022–1042.

Stratmann, T., Lins, L., Purser, A., Marcon, Y, Rodrigues, C., Ravara, A., Cunha, M.R., van Oevelen, D. (in prep.). Carbon flows in deep-sea food webs need more than twenty-six years to recover from an experimental disturbance in the Peru Basin.

Sunagawa S, Coelho LP, Chaffron S, Kultima JR, Labadie K, Salazar G, et al. (2015). Structure and function of the global ocean microbiome. Science 348(6237).

Sweetman, A. K., Thurber, A. R., Smith, C. R., Levin, L.A., Mora, C., Wei, C.-L., Gooday, A. J., Jones, D. O. B., Rex, M., Yasuhara, M., Ingels, J., Ruhl, H. A., Frieder, C. A., Danovaro, R., Würzberg, L., Baco, A. R., Grupe, B. M., Pasulka, A., Meyer, K. S., Dunlop, K. M., Henry, L.-A., Roberts, J. M., (2017). Major impacts of climate change on deep-sea benthic ecosystems, Elementa Science of the Anthropocene 5: 4, doi: 10.1525/elementa.203.

Taboada, S., Kenny, N.J., Riesgo, A., Wiklund, H., Paterson, G.L.J., Dahlgren, T.G., A.G. Glover. (in press). Mitochondrial genome and polymorphic microsatellite markers from the abyssal sponge *Plenaster craigi*: tools for understanding the impact of deep-sea mining. Marine Biodiversity.

Tamis, J.E., de Vries, P., Jongbloed, R., Lagerveld, S., Karman, C., Tjalling J., Van der Wal, J., Slijkerman, D.M.E., Klok, C. (2017). Toward a Harmonized Approach for Environmental Assessment of Human Activities in the Marine Environment Integr Environ Assess Manag 12, 2016.

Thiel, H., Schriever, G. (1990). Deep-Sea Mining, Environmental Impact and the DISCOL Project, Ambio 19(5). 245-250.

Thiel, H., Schriever, G., Ahnert, A., Bluhm, H., Borowski, C., Vopel, K., 2001. The large-scale environmental impact experiment DISCOL: reflection and foresight. Deep-Sea Research II 48, 3869-3882.

Thomsen, L., McCave, I.N. (2000). Aggregation processes in the benthic boundary layer at the Celtic Sea continental margin. Deep-Sea Research I, 47, 1389-1404.

Tsurusaki, K. (1997). Concept and Basic Design of the Plume Discharge. Proceedings, international symposium on environmental studies for deep-sea miningTokyo, Japan.

Turnewitsch, R., Falahat, S., Nycander, J., Dale, A., Scott, R.B., Furnival, D. (2013). Deep-sea fluid and sediment dynamics—Influence of hill- to seamount-scale seafloor topography. Earth-Science Reviews 127, 203-241.

Turnewitsch, R., Lahajnar, N., Haeckel, M., Christiansen, B. (2015). An abyssal hill fractionates organic and inorganic matter in deep-sea surface sediments. Geophysical Research Letters 42, doi:10.1002/2015GL065658.

van Doorn, E. (2016). Environmental aspects of the Mining Code: Preserving humankind's common heritage while opening Pardo's box? 70 Marine Policy (2016) 192-197.

Vanreusel, A., Hilario, A., Ribeiro, P.A., Menot, L., Martinez-Arbizu, P. (2016). Threatened by mining, polymetallic nodules are required to preserve abyssal epifauna. Scientific Reports 6, 26908.

Viarengo, A., Lowe, D., Bolognesi, C., Fabbri, E., Koehler, A. (2007). The use of biomarkers in biomonitoring: a 2-tier approach assessing the level of pollutant induced stress syndrome in sentinel organisms. Comp Biochem 146C, 281-300.

Volz, J., Mogollón, J., Geibert, W., Martínez Arbizu, P., Koschinsky, A., Kasten, S. (in prep.). Natural variability of geochemical conditions, biogeochemical processes and element fluxes in sediments of the eastern Clarion-Clipperton Zone, Pacific Ocean.

Vonnahme, T. R., Molari, M., Janssen, F., Wenzhöfer, F., Haeckel, M., Titschack, J., Boetius, A. (in prep.). Effects of simulated deep-sea mining impacts on microbial communities and functions in the DISCOL experimental area after 26 years.

Waller, R.G., Baco, A.R. (2007). Reproductive morphology of three species of deep-water precious corals from the Hawaiian archipelago: Gerardia sp., Corallium secundum, and Corallium lauuense. Bulletin of Marine Science, 533-542.

Wallmann, K., Haeckel, M., Linke, P., Haffert, L., Schmidt, M., Bünz, S., James, R., Hauton, C., Tsimplis, M., Widdicombe, S., Blackford, J., Queiros, A. M., Connelly, D., Lichtschlag, A., Dewar, M., Chen, B., Baumberger, T., Beaubien, S., Vercelli, S., Proelss, A., Wildenborg, T., Mikunda, T., Nepveu, M., Maynard, C., Finnerty, S., Flach, T., Ahmed, N., Ulfsnes, A., Brooks, L., Moskeland, T., Purcell, M. (2015). Best Practice Guidance for Environmental Risk Assessment for offshore CO2 geological storage, ECO2 Deliverable D14.1, 53 p.

Weaver, Phil et al. (2016). Managing Impacts of Deep Sea Resource Exploitation: The MIDAS Project. Research Highlights, www.eu-midas.net. [31.10.2017]

Wedding, L.M., Friedlander, A.M., Kittinger, J.N., Watling, L., Gaines, S.D., Bennett, M., Hardy, S.M., Smith, C.R. (2013). From principles to practice: a spatial approach to systematic conservation planning in the deep sea. Proceedings of the Royal Society B: Biological Sciences 280 (1773).

Wiklund, H., Taylor, J.D., Dahlgren, T.G., Todt, C., Ikebe, C., Rabone, M., Glover, A.G. (in press). Abyssal fauna of the UK-1 polymetallic nodule exploration area, Clarion-Clipperton Zone, central Pacific Ocean: Mollusca. Zootaxa.

Witte, U., Wenzhöfer, F., Sommer, S., Boetius, A., Heinz, P., Aberle, N., Sand, M., Cremer, A., Abraham, W.-R., Jørgensen, B. B., Pfannkuche, O. (2003). In situ experimental evidence of the fate of a phytodetritus pulse at the abyssal sea floor. Nature 424: 763–766.

Yamazaki, T., Barnett, B.G., Suzuki, T. (1997). Optical determination of the JET deep sea sediment disturbance. Proceedings of the International Symposium on Environmental Studies for Deep-Sea Mining, Tokyo, Japan, 153-167.

Zinger, L., Amaral-Zettler, L. A., Fuhrman, J. A., Horner-Devine, M. C ., Huse, S. M., Mark Welch, D. B., Martiny, J. B. H., Sogin, M., Boetius, A., Ramette, A. (2011). Global patterns of bacterial beta-diversity in seafloor and seawater ecosystems, PLoS ONE 6: e24570.